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Comparative life-cycle cost analysis of refrigeration systems in ice rinks

Master of Science thesis

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Abstract of master's thesis

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Abstract

Ice rinks consume a lot of energy. Statistics from Sweden show that a typical ice rink needs about 1 000 000 kWh purchased energy annually, with the refrigeration system accounting for about 43%. Because a large number of ice rinks, for example more than 70 of documented ice rinks in Finland, do not fulfill the requirements of the updated F-gas Regulation set by the EU for greenhouse gases, subsequent renovations will require sound financial decision-making in order to improve their overall performance. Hence the concept of life-cycle cost (LCC) analysis has been increasingly applied to estimate costs. However, a practical way to incorporate the concept when comparing the economic performances of refrigeration systems still seems to be missing. The objective of this study is to address this issue by developing an LCC analysis model that is effective and capable of producing reliable results when comparing refrigeration systems in ice rinks.

The LCC model is developed in Excel with programmed macro commands that automatically perform calculations and LCC analysis. Different tools are included in the model in order to critically evaluate the input data and to provide a broad view of refrigeration system performance. The model is applied to a real case in Sweden, where the LCC analysis concludes that installing a CO_2 indirect system with a heat export function would yield the best financial results and should therefore replace the existing refrigeration system of the ice rink.

Results indicate that the sensitivity and scenario analysis plays a crucial role when evaluating the quality of input data. The reliability and robustness of calculated results can therefore be assessed, which demonstrates the applicability of the developed model in comparative LCC analysis of refrigeration systems in ice rinks. Furthermore, the limitations of this thesis, such as the number of systems analyzed simultaneously, and suggestions for future research, including model expansion, documentation, and presentation of results, are also discussed.

Keywords CO_2, Ice rink, Life-cycle cost, Refrigerant, Refrigeration system

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Sammandrag

Ishallar använder stora mängder energi och i en svensk studie konstateras energianvändningen vara cirka 1 000 000 kWh per år för en genomsnittlig ishall, där kylsystemet står för omkring 43% av den totala konsumtionen. Eftersom många ishallar, t.ex. mer än 70 av de dokumenterade ishallarna i Finland, inte uppfyller de krav som den nya F-gasförordningen i EU ställer på växthusgaser, står många anläggningar inför ändringar i sina kylsystem inom en snar framtid. Detta kommer att kräva långsiktigt ekonomiskt beslutsfattande, där konceptet livscykelkostnadsanalys (LCC) har ökat i användning för att estimera kostnader. Dock har man inte än lyckats integrera konceptet på ett praktiskt sätt då man jämför ekonomiska prestationer hos kylsystem. Syftet med denna studie är att utveckla en LCC-modell som är effektiv samt kapabel av att skapa trovärdiga resultat då man jämför kylsystem i ishallar.

LCC-modellen är utvecklad i Excel med programmerade makrofunktioner som automatiskt utför uträkningar och LCC analys. Olika verktyg är inkluderade i modellen med syftet att kritiskt utvärdera input data samt ge en bred uppfattning gällande ett kylsystems prestationsförmåga. Modellen appliceras i en fallstudie i Sverige, där resultaten i LCC-analysen indikerar att ett indirekt CO_2-system med värme export vore den bästa lösningen ur en ekonomisk synvinkel och borde därför ersätta det befintliga kylsystemet i ishallen.

Resultaten visar att känslighets- och scenarioanalysen spelar en avgörande roll då man utvärderar kvaliteten på input data. Trovärdigheten samt hållbarheten av uträknade resultat kan således fastställas, vilket bevisar att den utvecklade LCC-modellen kan tillämpas vid komparativ LCC analys av kylsystem i ishallar. Vidare diskuteras studiens begränsningar, t.ex. antalet system som simultant kan analyseras, samt anges rekommendationer för fortsatta studier där en expansion av modellen, dokumentation, och presentation av resultaten ingår.

Nyckelord CO_2, Ishall, Kylsystem, Köldmedium, Livscykelkostnad

Preface

The choice for this thesis topic was a result of my personal interest in sustainable development, both from the environmental and the financial perspective. The study was conducted in cooperation with EKA in Sweden with backing from the Foundation for Aalto University Science and Technology.

I'd especially like to thank Professor Xiaoshu Lü for her patience, kindness and support over the last years. The positive energy has helped me a lot, and motivated me to do my best.

I'd also like to give special thanks to Jörgen Rogstam at EKA for his expertise, views, and encouragement while this study was conducted. Working with someone who's passion is related to energy efficiency is simply awesome.

Thanks to Simon Bolteau at EKA for his help whenever there was something about refrigeration that I didn't understand. And for the occasional singing at the office.

Last but not least, I want to thank my family and friends for their support over all these years that I've been studying at Aalto University.

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Abbreviations

ASHRAE	American Society of Heating, Refrigerating, and Air-conditioning Engineers
BLEVE	Boiling liquid expanding vapor explosion
CO	Carbon monoxide
CO_2	Carbon dioxide
COP	Coefficient of performance
DH	District heating
EAC	Equivalent annual cost
GWP	Global warming potential
HFC	Hydrofluorocarbon
HTP	Hazardous concentration value
HP	Heat pump
IIHF	International ice hockey federation
LCC	Life-cycle cost
LCA	Life-cycle assessment
LED	Light-emitting diode
NH_3	Ammonia
NO	Nitric oxide
ODP	Ozone depletion potential
PPM	Parts per million
PV	Present value
SEK, kr	Swedish Krona
VTT	State technical research center of Finland

1. Introduction

1.1. Background information

Ice rinks consume a lot of energy. Results from measurements done in Sweden indicate that the operation of an average ice rink requires about 1 000 000 kWh purchased energy per year. The refrigeration system, usually employing an effect of 250-350 kW, covers circa 43% of the energy demand and is therefore the largest consumer. (Rogstam;Beaini;& Hjert, 2014)

In order to further control emissions from fluorinated greenhouse gases (F-gases), the European Union updated in 2015 the F-gas Regulation, where refrigerants with high global warming potential (GWP) are to be gradually phased out and replaced by substances that fulfill the environmental requirements. A group of refrigerants highly affected by the F-gas Regulation are the synthetic hydrofluorocarbons (HFCs), which have been very popular in ice rink refrigeration systems over the last decades. (European Comission, 2016)

The state technical research center of Finland (VTT) has documented which refrigerants are used in 150 out of the 223 ice rinks in Finland. Of the documented cases, more than 70 have HFC-based refrigeration systems that don't fulfill the GWP-requirements stated by the F-gas Regulation. This means that many facilities will be facing renovations in the near future. Furthermore, there are up to five new ice rinks built in Finland each year that naturally must fulfill the GWP-requirements in their chosen technologies. (VTT, 2016)

Due to the increased awareness of climate change and the recent adoption of the F-gas Regulation, natural refrigerants have started to gain more interest as they are seen as long-term solutions. Refrigeration systems based on ammonia (NH_3) are well documented and have also been popular in Finland. Lately however carbon dioxide (CO_2) has emerged as an alternative, where the properties of the substance make it especially well-suited for situations where there is a combined refrigeration and heating demand.

An ice rink in Sweden became in 2014 the first in Europe to implement a refrigeration system that is fully based on CO_2. The technology allows for the effective use of a heat recovery system that covers the entire heating demand of the facility. As a result, the energy consumption of the ice rink went down by more than half of what it had been before which means that remarkable savings were made in operating cost. These foreseen benefits along with estimations in investment and service cost had previously been taken into account in a comparative life-cycle cost (LCC) analysis, where calculations had shown that the CO_2-based system was the most economic option for the ice rink. The results had consequently served as the basis for the municipality's decision to invest in the new climate-friendly technology. (Rogstam & Bolteau, 2015)

1.2. Problem description

A common pitfall in financial decision-making is applying simple methods that exaggerate the focus on investment cost and don’t give enough attention to operating and service costs, especially if there is a long economic lifespan involved. An LCC analysis corrects this mistake by including all the costs that occur during the life cycle of a technological solution when calculating the financial performance. This allows for the reliable discovery of the most profitable option from a holistic perspective when comparing results. (ASHRAE, 2015)

The LCC analysis methodology is however not yet widely used in financial decision-making, mainly for two reasons. Firstly, the input data is often based on estimations that may lead to unreliable results if not treated properly. Secondly, a thorough LCC analysis with conclusive results typically requires a lot of work. Simpler methods are therefore commonly applied in financial decision-making, e.g. in municipalities, which increases the risk of not selecting the most profitable solution.

The problem could be remedied if there were a way to make the LCC analysis process more practical, while still being able to generate reliable results. This means that the process should be tailored to a specific context in order to be effective. A state of the art LCC analysis model that compares refrigeration system performance in ice rinks is therefore in demand.

1.3. Objective

The objective of this study is to develop an LCC analysis model that is effective and capable of producing reliable results when comparing refrigeration systems in ice rinks. The model is to be tested in a case setting, where a municipality in Sweden has requested to evaluate options for replacing the existing refrigeration system in its ice rink.

1.4. Method

The study begins with a literature review, where the technology used ice rinks is examined and the logic behind the LCC analysis methodology is investigated. A chapter before that has been dedicated to the revision of the properties of CO_2 from a refrigerant perspective, due to the recent entry of the substance on the European ice rink market.

The LCC analysis model is developed in Excel and makes use of programmed macro commands together with linked input data, which automates calculations and lowers the workload considerably when conducting a thorough LCC analysis. Different analysis tools are included in order to critically evaluate the input data while also giving a broader picture of refrigeration system performance. The application of the model should therefore ease the process of sound financial decision-making.

The LCC analysis model is tested in a case setting, where the current state of an ice rink in Sweden is initially reviewed. Based on gathered information, new refrigeration system solutions are suggested for the facility. Ultimately the financial performances between the existing refrigeration system and potential replacements are compared.

1.5. Scope and limitations

Heat recovery from a refrigeration system plays an important part in the energy efficiency of an ice rink by lowering the energy consumption of other heat sources. In order to recognize the benefits of heat recovery, this study will include heating strategies when evaluating the performance between refrigeration systems. The LCC analysis will therefore analyze system solutions that fulfill both the refrigeration and heating demands of an ice rink.

The new refrigeration system solutions suggested for the case ice rink are only based on the natural refrigerants NH_3 and CO_2. While there are HFC-based refrigerants that still fulfill the requirements of the current F-gas Regulation, they are not seen as long-term solutions as the risk remains that they will be phased out in the future. Refrigeration systems based on the natural medium propane are available, but won't be analyzed in this study due to the high fire hazard of the substance.

This study has limited its scope to LCC analysis only and will focus on the cost-effectiveness of a system solution, since the analyzed refrigeration systems in the real case are all based on natural refrigerants that are seen as long-term solutions in terms of sustainability. However, an LCC analysis is typically part of a Whole-life cost analysis where the environmental and social impacts as well as risks are also included in the form of a life-cycle assessment (LCA). An expansion of the developed LCC analysis model will therefore be suggested for future research, in order to turn it into a Whole-life cost analysis model that can be used in broader contexts as well.

2. CO_2 as refrigerant

2.1. Historical information

Carbon dioxide has been used as a refrigerant in various types of vapor compression systems for more than 140 years. When it was introduced as a refrigerant, CO_2 became a popular choice with the reason being that its combination of efficiency, reliability, and safety was preferred over that of the other natural refrigerants available on the market. However, the initial development of carbon dioxide as a refrigerant was quite slow due to lack of scientific data and appropriate technology to be used with the substance. (Pearson, 2005)

The use of CO_2 came more or less to a halt in the 1930s after the entry of man-made synthetic chemical refrigerants that managed to combine the best characteristics of the natural refrigerants that had preceded them. In comparison to CO_2 the switch to synthetic refrigerants resulted in a lower working pressure, possibility to use heat exchangers that were lighter and would be of lower cost, and a better cooling capacity in high ambient temperatures. Synthetic refrigerants also enjoyed aggressive marketing campaigns that made the man-made substances the mainstream option. (Padalkar & Kadam, 2010)

Synthetic refrigerants were generally accepted as the safest choice for many years after their introduction. But during the last decades of the 20th century environmental concerns started to emerge around the world, requiring a reevaluation of refrigerant properties. When tools to assess environmental impact were implemented in scientific research, results began to appear showing that popular synthetic refrigerants were having a considerable effect on ozone layer depletion and global warming. This led scientists to focus on the development of new and improved refrigerants that would minimize the harmful effects on the environment. (Padalkar & Kadam, 2010)

While improved synthetic refrigerants have appeared throughout the years of environmental awareness, scientific communities have also been inspecting new ways to handle natural refrigerants that would make them competitive alternatives to the man-made substances. Carbon dioxide received attention once again in the 1990s when new scientific discoveries and the development of modern techniques introduced new ways to exploit the uniquely beneficial properties of the substance, mainly in the supercritical fluid region of the substance. The amount of scientific papers that focus on the use of CO_2 as a refrigerant has increased substantially ever since. Furthermore, recent developments in international codes and legislation have made carbon dioxide quite a preferred choice. The reason for the increased popularity is that there is little worry that CO_2 will be phased out in the future, something that currently is happening to the once popular synthetic refrigerant R-22. (Pearson, 2005)

2.2. Properties

2.2.1. Environmental impact

Table 1 shows the environmental impacts of the main refrigerants that currently are in use. The global warming potential (GWP) is a relative measure of how much heat the listed refrigerants trap in the atmosphere and is expressed as a factor of carbon dioxide, therefore giving CO_2 the base value of 1. The ozone depletion potential (ODP) of the refrigerants is the relative amount of degradation they can cause to the ozone layer, with trichlorofluoromethane (R-11) having the base value of 1. The GWP in particular, which measures the importance of the greenhouse effect, emphasizes the considerable advantage that CO_2 and NH_3 have over synthetic refrigerants in terms of impact on the environment. (CanmetENERGY, 2013)

Refrigerant	Components	GWP(1)	ODP(2)
R-717	**Ammonia**	**0**	**0**
R-744	**Carbon dioxide (CO_2)**	**1**	**0**
CFC-R11	Pure	3800	1.0
CFC-R12	Pure	8100	1.0
HCFC-R22	**Pure**	**1810**	**0.055**
HCFC-R123	Pure	76	0.012
HFC-R134A	**Pure**	**1430**	**0**
HFC-R404A	**R -125 /143A/134A**	**3900**	**0**
HFC-R407A	R-32/125/134A	2100	0
HFC-R407c	R-32/125/134A	1800	0
HFC-R410A	R-32/125	1725	0
HFC-R417A	R-125/134A/600	2300	0
HFC-R422A	R-125/134A/600A	3100	0
HFC-R422d	R-125/134A/600A	2700	0
HFC-R427A	R-32/125/143A/134A	2100	0
HFC-R507A	**R-125 /143A**	**4000**	**0**

Legend:
Bold font = frequently used in ice rinks
(1) GWP: Global-warming potential
(2) ODP: Ozone depletion potential

Table 1: Main refrigerants and their environmental impacts. (CanmetENERGY, 2013)

2.2.2. Thermo-physical properties

The phase diagram for CO_2 is shown in Figure 1. A characteristic that separates carbon dioxide significantly from other refrigerants is its critical point, with a relatively low temperature of 31,06°C and a high pressure of 73,8 bar. In the sub-critical region, pressure and temperature are coupled and there is a clear distinction between the two phases of gas and liquid. This is not the case above the critical point. In the super-critical region, the distinction disappears and the state can no longer be caller liquid nor gas. It is commonly referred to as supercritical fluid instead. The heat rejection of a supercritical fluid takes place at a constant pressure while the temperature changes are similar to that of single phase. The triple point of carbon dioxide lies at -56,6°C and 5,2 bars. A pressure value below 5,2 bars results in a non-liquid state of CO_2 meaning that the value also acts as the lower pressure limit for a refrigeration cycle. From all this it can be concluded that a refrigeration cycle using CO_2 will have a high operating pressure while heat rejection will take place in the super-critical region when the ambient temperature is high. (Sawalha, 2008)

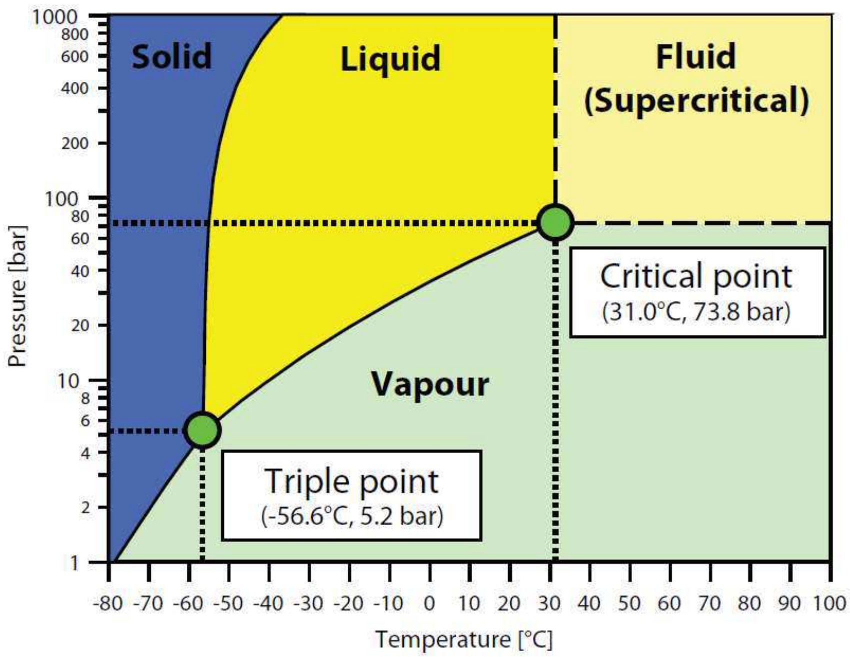

Figure 1: Phase diagram for CO_2. (Danfoss, 2008)

High operating pressure is an important feature that distinguishes CO_2 from other refrigerants. Carbon dioxide has at 0°C a pressure which is about 6 times higher than that of R404A and 7 times higher than that of NH_3, as can be seen in Figure 2. The high operating pressure further results in two significant thermo-physical advantages that CO_2 has in its refrigeration cycle: high vapor density and low vapor pressure drop. (Sawalha, 2008)

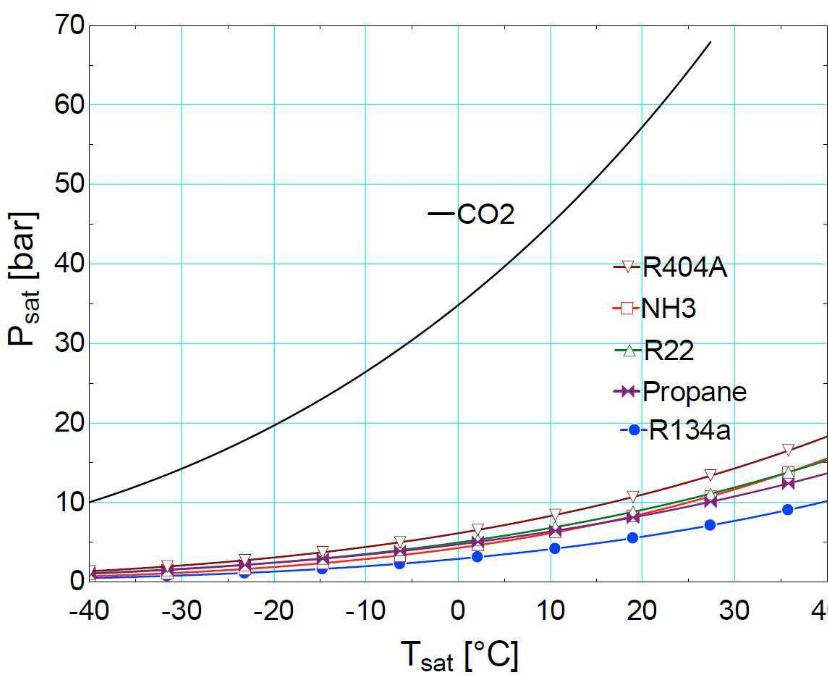

Figure 2: Saturation pressure versus temperature for selected refrigerant. (Sawalha, 2008)

A higher vapor density is an advantage in the sense that it increases the volumetric refrigeration effect. This means that a smaller refrigerant vapor volume flow rate is needed for CO_2 in order to achieve the same cooling capacity as other refrigerants. Figure 3 illustrates the magnitude of the advantage. (Sawalha, 2008)

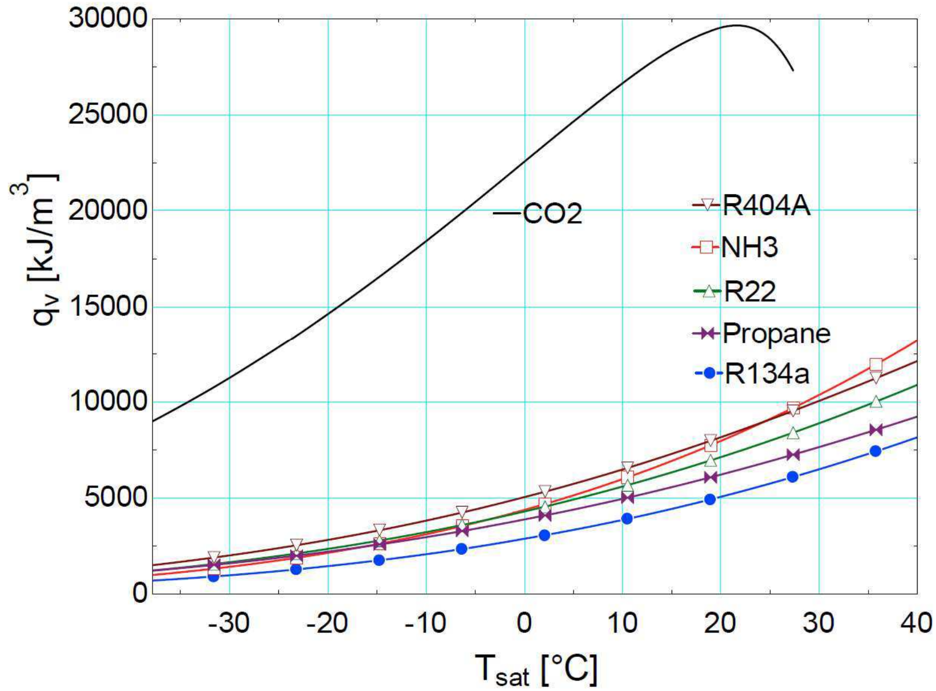

Figure 3: Volumetric refrigeration capacity. (Sawalha, 2008)

Low vapor pressure drop has the benefit that it allows for the use of smaller components and more compact distribution lines. The pressure drop can be expressed as a function of the density and the volumetric refrigeration effect as shown in Equation 1:

$$\Delta P = \frac{1}{q_v \times h_{fg}} \times Y$$

Equation 1: Pressure drop function (Sawalha, 2008)

where q_v is the volumetric refrigeration capacity $\left(\frac{kJ}{m^3}\right)$, h_{fg} is the latent heat of vaporization $\left(\frac{kJ}{kg}\right)$, and Y is a constant $\left(\frac{kW^2}{m^4}\right)$ that includes the parameters related the geometry of the refrigeration system and operating conditions. By assuming identical geometry and operating conditions for all refrigerants, Y can be excluded when comparing the pressure drop between refrigerants. Refrigerant pressure drop in relation to CO_2 is shown in Figure 4. (Sawalha, 2008)

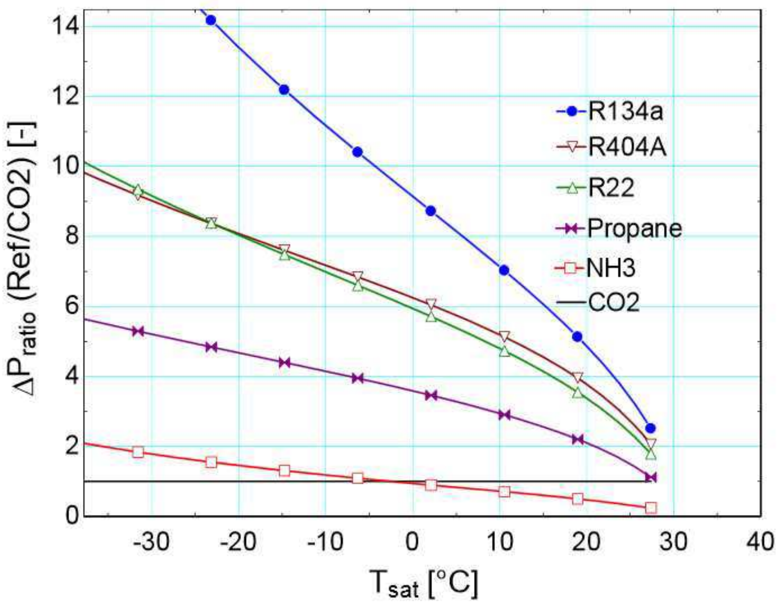

Figure 4: Vapor pressure drop ratio in comparison to CO_2 at different saturation temperatures. (Sawalha, 2008)

By observing Figure 4 with Equation 1 in mind it can be concluded that the high volumetric refrigeration capacity q_v of CO2 contributes substantially to the low pressure drop of the substance when compared to other refrigerants, since most refrigerants have values for latent heat of vaporization h_{fg} that lie in the same range as the substance. Ammonia however is different because its values for latent heat of vaporization as shown in Figure 5 are exceptionally high in comparison to the rest, which leads to NH3 having a lower pressure drop than CO2 at temperatures higher than 0°C. (Sawalha, 2008)

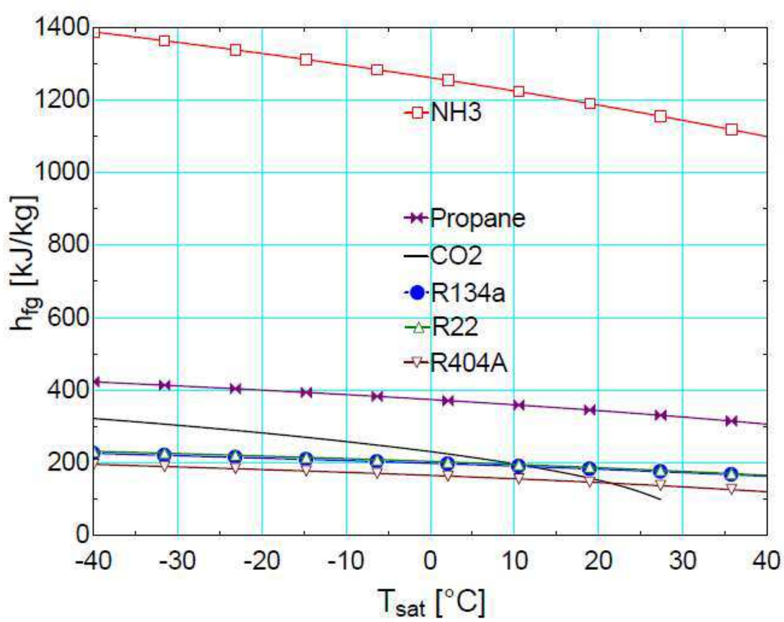

Figure 5: Latent heat of vaporization/condensation for selected refrigerants. (Sawalha, 2008)

The resulting effect of a pressure drop is a drop in the saturation temperature of the refrigerant, which has a negative effect on the coefficient of performance (COP) of the system. CO_2 has a favorable position in this matter as well in comparison with other refrigerants since both a low pressure drop and a high volumetric refrigeration capacity generate a lower temperature drop, as observed in Equation 2:

$$\Delta T_{sat} = T_{abs} \times \frac{1}{q_v} \times \Delta P$$

Equation 2: Saturation temperature drop. (Sawalha, 2008)

where T_{abs} is the absolute temperature of the fluid (K) which assumes the same value for all substances when comparing refrigerants. (Sawalha, 2008)

The advantages gained due to the lower temperature drop coupled with the low pressure drop and high volumetric refrigeration capacity further justify the use of smaller and more compact components in the case of CO_2. This gives the substance further leverage in applications where space saving is required or in applications where cost savings can be considerable due to lower material use. (Sawalha, 2008) The latter advantages are usually offset by the requirement to use steel pipes with CO_2 due to the high pressure in the system while synthetic refrigerants only require plastic pipes in their distribution systems. Research and installations with CO_2 show however that the use of copper pipes is also a feasible option that can lead to a lower cost and payback time than the use of steel pipes. (Rogstam;Sawalha;& Nilsson, 2005)

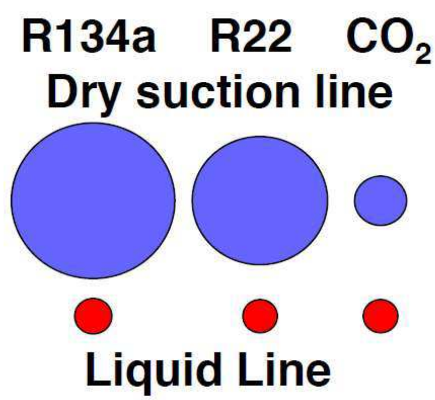

Figure 6: Relative sizing of pipes to give the same capacity. (Funder-Kristensen, 2012)

In terms of thermal behavior in the subcritical region, CO_2 has several properties in its favor. It has a relatively high thermal conductivity for gas and liquid and a high specific heat. (Sawalha, 2008) Furthermore, carbon dioxide has the lowest ratio of liquid to vapor density in comparison to other refrigerants as shown in Figure 7. Close to the critical point the density difference between the two states gets very low which increases the momentum for the vapor phase, improves the shear force between the liquid and vapor flows, and ultimately leads to a more homogenous flow pattern. Due to these factors, CO_2 has a heat transfer coefficient that is significantly higher than that of other refrigerants except ammonia. (Padalkar & Kadam, 2010)

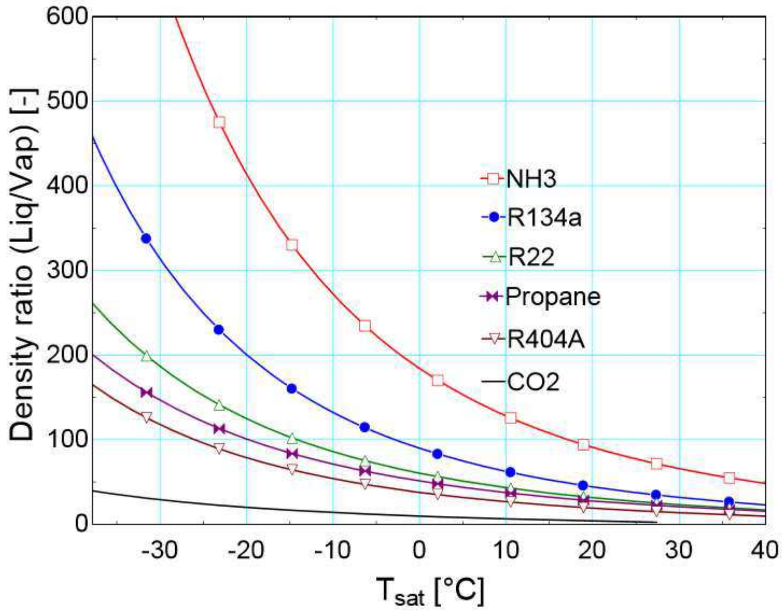

Figure 7: Liquid to vapor density ratios at different saturation temperatures. (Sawalha, 2008)

2.2.3. Transcritical operation

Figure 8 shows the subcritical refrigeration process to the left and the transcritical refrigeration process to the right. The main difference between the two cycles is how their respective heat rejection parts work. In the subcritical cycle heat rejection occurs below the critical point, which allows for condensation of the refrigerant at constant pressure and temperature. In the transcritical cycle heat rejection occurs above the critical point, i.e. in the supercritical fluid region of the refrigerant. This means that there is no condensation involved in the heat rejection, but instead the cooling of gas in the supercritical fluid region where the temperature of the refrigerant changes constantly. (Danfoss, 2008)

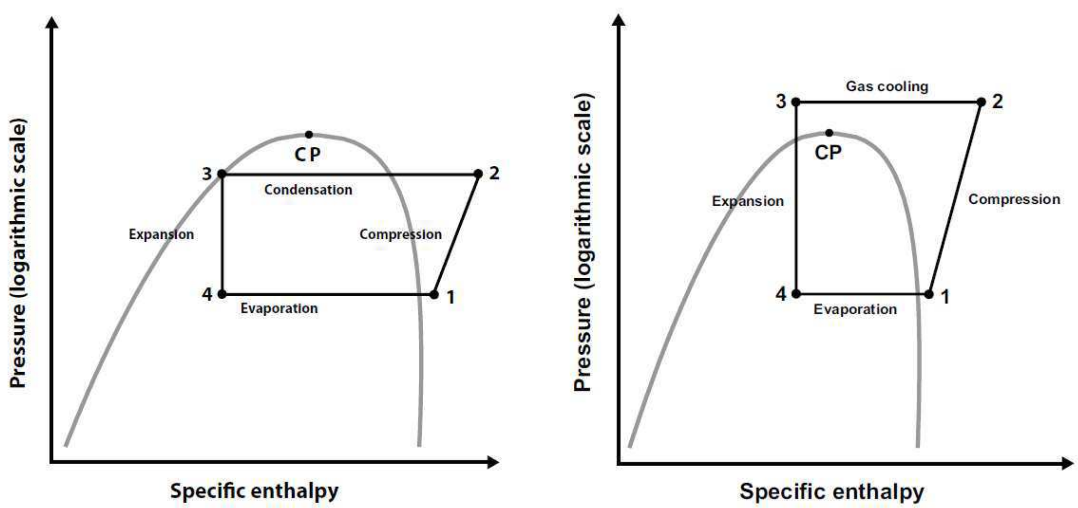

Figure 8: Subcritical and transcritical refrigeration processes. (Danfoss, 2008)

Typical refrigerants have a critical temperature around 90°C, which makes the subcritical cycle more traditional in most refrigeration applications where heat is rejected to the atmosphere. CO_2 however, as shown in Figure 1, has a critical temperature much lower than that which makes the transcritical cycle necessary in applications where ambient temperatures can exceed 25°C. (Danfoss, 2008)

Since heat rejection in the transcritical cycle does not involve a phase change process of the refrigerant, the pressure won't be determined by the saturation pressure of the substance as is the case in the subcritical cycle during condensation. Instead the gas cooler pressure is determined by the charge of the refrigerant, meaning that the pressure and temperature become independent. The effect the gas cooler pressure has on the COP of the refrigeration system is illustrated in Figure 9. (Danfoss, 2008)

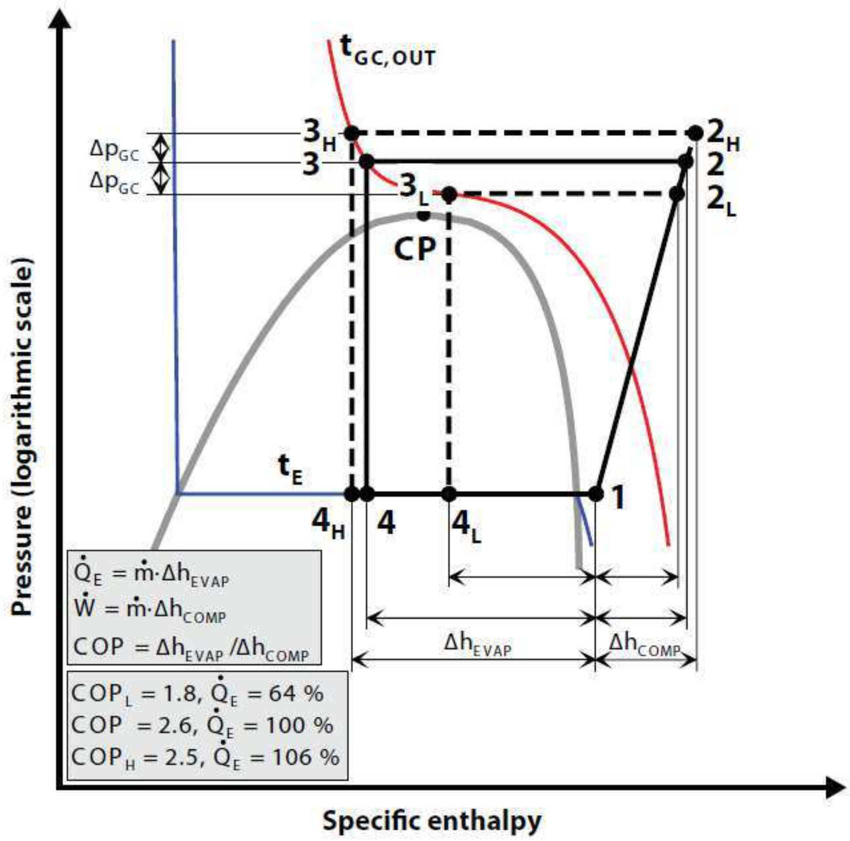

Figure 9: Influence of gas cooler pressure on COP. (Danfoss, 2008)

Figure 9 shows that small changes in the gas cooler pressure Δp_{GC} can have a significant impact on the refrigeration capacity, determined by changes in the specific enthalpy in the evaporator Δh_{EVAP}, and also influence the compressor power consumption, determined by changes in the specific enthalpy in the compressor Δh_{comp}. The resulting effects lead to changes in the COP of the system. The changes can be for the worse regardless of lowering or increasing the pressure, as indicated in Figure 9, meaning that an optimum gas cooler pressure exists when striving to maximize the COP of a transcritical operation. Moreover, it can be observed that the maximum COP of the system does not entail the maximum value of the refrigeration capacity $\dot{Q}_E$, confirming discharge pressure control as the main tool for maximizing system performance. (Danfoss, 2008)

In Figure 10 it is demonstrated that the optimum gas cooler pressure varies with the gas cooler exit temperature, which is directly affected by the ambient temperature. Since the operating conditions will vary for the vast majority of practical applications, changes in discharge pressure are needed in order to keep COP at maximum. An optimum pressure formula has been calculated, and can be found in Equation 3:

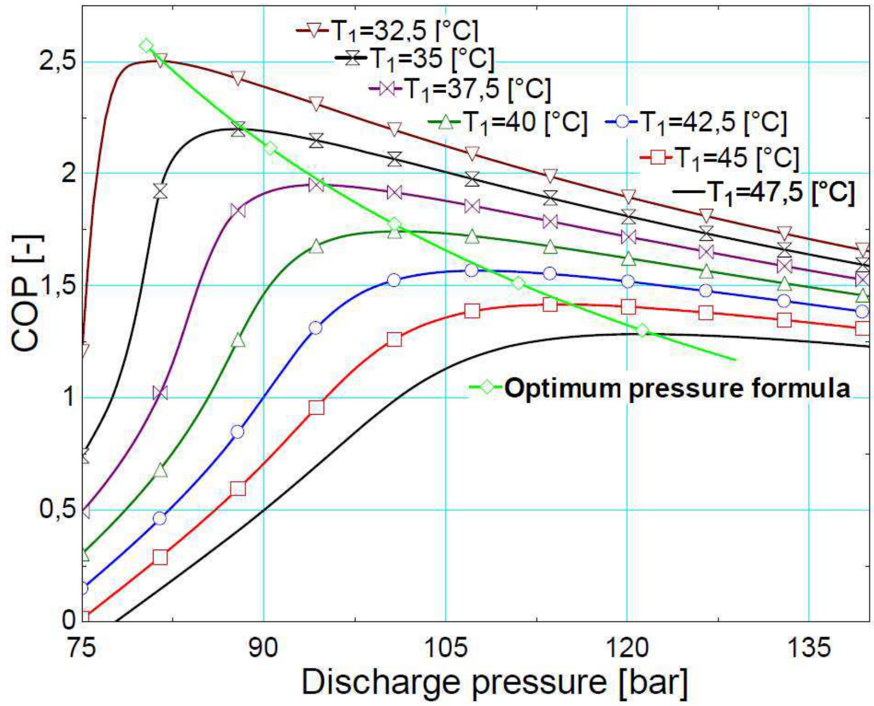

Figure 10: COP of CO_2 transcritical cycle in relation to discharge pressure at different gas cooler exit temperatures. (Sawalha, 2008)

$$P_{opt} = 2{,}7 \times T_{Gas\ cooler,Exit} - 6{,}1$$

Equation 3: Optimum discharge pressure formula. (Sawalha, 2008)

where $T_{Gas\ cooler,\ Exit}$ (°C) decreases with lower ambient temperature, leading to a lower optimum discharge pressure P_{opt} (bar) and vice versa. (Sawalha, 2008)

Compared to the subcritical cycle, the operation of a transcritical cycle in itself will create a loss in cooling capacity and also lead to a higher power consumption in the compressor. A loss of refrigerant COP is therefore inevitable and it gets worse as the ambient temperature rises. However, in comparison to other refrigerants the discharge gas of CO_2 is warmer and stores a higher energy density due to the higher pressure and higher volumetric refrigeration capacity of the substance. (Sawalha, 2008) Therefore, the heat recovery potential of the CO_2 vapor is much higher than that of other refrigerants, improving its transcritical performance to competitive levels with e.g. NH_3 in systems where heat recovery is properly utilized (Rogstam;Abdi;& Sawalha, 2014).

2.3. Safety

Carbon dioxide is a relatively safe refrigerant when compared to other natural and artificial substances. In the ASHRAE Handbook-Fundamentals (ASHRAE, 2005), CO_2 is classified in group A1 where included substances are considered to be the least hazardous and without any identified toxic effects at concentrations below 400 Parts Per Million (PPM). Carbon dioxide exists naturally in the atmosphere at concentrations around 350 PPM and for concentrations between 300 and 600 PPM people usually don't notice any difference. (Sawalha, 2008)

Table 2 shows how different concentrations of CO_2 affect human health. According to the Finnish guide for air-conditioning Sisäilmastoluokitus (Sisäilmayhdistys, 2009), a CO_2 concentration below 1200 PPM is necessary in order to fulfill the requirements for a healthy and comfortable environment in a building. Lower concentrations are preferred and ASHRAE (ASHRAE, 1989) recommends a limit of 1000 PPM in order to ensure the comfort for the occupants.

PPM	Effects on health
350	Normal value in the atmosphere
1,000	Recommended not to be exceeded for human comfort
5,000(1)	TLV-TWA(2)
20,000	Can affect the respiration function and cause excitation followed by depression of the central nervous system. 50% increase in breathing rate
30,000(3)	100% increase in breathing rate after short time exposure
50,000 (40,000)(4)	IDLH(5) value
100,000	Lowest lethal concentration
	Few minutes of exposure produces unconsciousness
200,000	Death accidents have been reported
300,000	Quickly results in an unconsciousness and convulsions

(1) The Occupational Safety and Health Administration (OSHA) revised Permissible Exposure Limit (PEL): Time-Weighted Average (TWA) concentration that must not be exceeded during any 8 hour per day 40 hour per week

(2) Threshold Limit Value (TLV): TWA concentration to which one may be repeatedly exposed for 8 hours per day 40 hours per week without adverse effect.

(3) Short Term Exposure Limit (STEL): a 15-minute TWA exposure that should not be exceeded at any time during a workday

(4) National Institute for Occupational Safety and Health (NIOSH) revised Immediately Dangerous to Life or Health (IDLH) value

(5) IDLH: maximum level for which one could escape within 30 minutes without any escape-impairing symptoms or any irreversible health effects.

Table 2: Expected health consequences for different concentrations of CO_2. (Sawalha, 2008)

The Decree on Concentrations Known to be Hazardous, issued by the Finnish Ministry of Social Affairs and Health in order to promote occupational safety, lists 5000 PPM as the hazardous concentration value, or HTP-value, for CO_2 when exposed to the substance for up to eight hours a day. For a 15-minute short time exposure there is no given HTP-value in the Finnish reference although international references give CO_2 a corresponding HTP-value of 30000 PPM, as indicated in Table 2. NH_3 has much smaller HTP-values, for an eight-hour exposure it is 20 PPM and for a 15-minute exposure it is 50 PPM, indicating a clear difference on how well the two refrigerants are tolerated by humans. (Sosiaali- ja Terveysministeriö, 2014)

The main drawback for CO_2 from a safety perspective is that it is odorless and lacks color. In comparison to NH_3, which has a pungent smell at concentrations well below its own HTP-values, CO_2 concentrations can reach dangerous levels without detection by the human sensory system. Simulations have shown that even lethal concentrations are possible in confined spaces that require a large amount of refrigeration, especially at lower levels close to the source of the leakage where the CO_2 has pooled due to its high density in comparison to air (CanmetENERGY, 2013). Facilities where CO_2 may leak must therefore be equipped with sensors that trigger an alarm when HTP-values are exceeded, especially in places where leakages are possible and high local concentrations are expected in case of a leak. (Sawalha, 2008)

When investigating the risks for rupture or explosion, the relatively high operating pressure of CO_2 presents higher requirements for the components and the distribution system in terms of material choice and thickness. The explosion energy depends however on the energy released by the expansion of the refrigerant in the system. Due to its high volumetric refrigeration capacity, the use of CO_2 requires a much smaller charge and therefore its explosion energy won't be bigger than that of e.g. R-22. (Padalkar & Kadam, 2010) Additionally, the risk for a boiling liquid expanding vapor explosion (BLEVE), which may create a more severe blast effect than that of an ordinary refrigerant expansion, is deemed improbable in the case of CO_2 whereas the use of NH_3 can produce such explosions while under pressure to fire (CanmetENERGY, 2013).

2.4. Applications

Europe is the market leader for natural refrigerants and CO_2 has been successfully implemented in various refrigeration applications on the continent. The applications can be grouped into the following sectors: (Shecco, 2014)

- Food chain
- Industry
- City, Building & Transport
- Sports

2.4.1. Food chain

The food chain sector is by far the largest of the four, accounting for about 75% of the European industrial refrigeration capacity. The move towards a broader adaption of natural refrigerants is continuing throughout Europe due to legislation, and CO_2 is becoming increasingly competitive on the market. Various production facilities and distribution systems have implemented CO_2: ice cream makers, slaughterhouses, breweries, food storages, marine containers, etc. (Shecco, 2014)

The clearest shift towards CO_2 refrigeration however can be observed in large-format stores and convenience stores. As shown in Figure 11, the amount of CO_2 transcritical stores has more than doubled up to almost 3000 in only two years. The Nordic countries are leading the development, especially Denmark with its stricter GWP policies than those of EU. One of Finland's largest retailers has begun to put CO_2 transcritical systems into use in its stores, resulting in the high growth rate in the country. (Shecco, 2014)

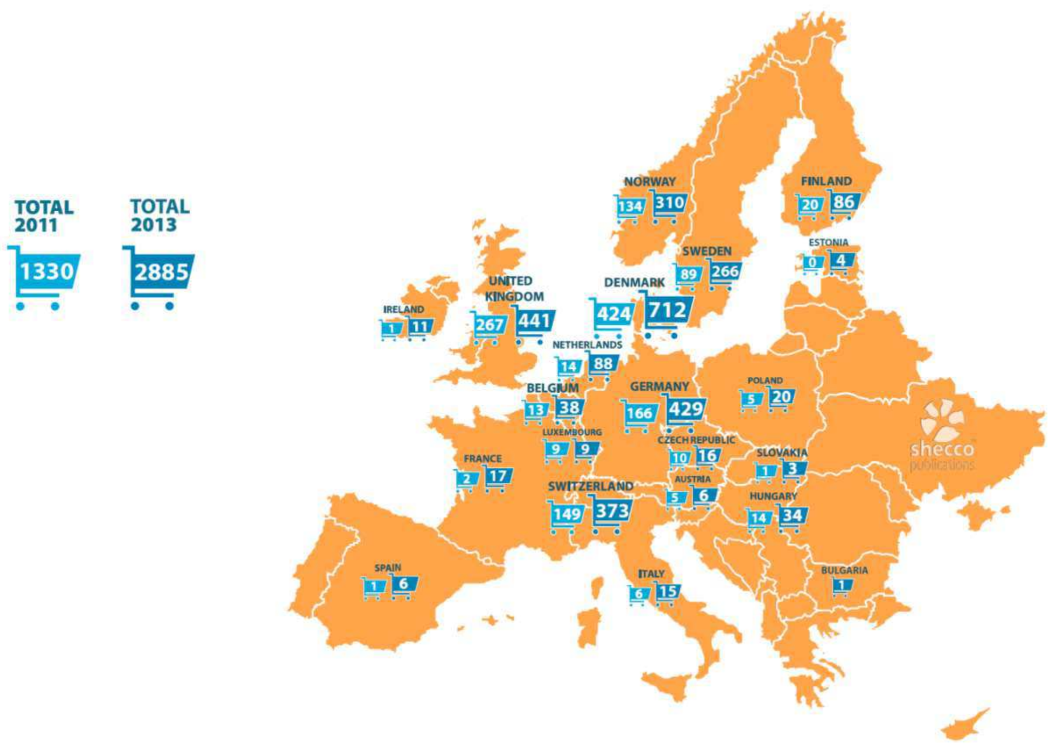

Figure 11: Map of CO_2 transcritical stores in Europe. (Shecco, 2014)

Surveys predict that CO_2 will become a mainstream solution for the commercial refrigeration sector, if not the market leader, by 2020. Considered a cheap and relatively safe refrigerant with low operation costs, CO_2 is also viewed as a good alternative for the food industry in the long run due to its low environmental impact and green image (Funder-Kristensen, 2012). Furthermore, the higher investment costs are expected to become competitive in the future thanks to increased competition, as more suppliers and experts enter the market bringing with them new innovations and economies of scale. Reported results after implementation so far have shown a reduction in energy consumption by 20-30%, while CO_2 emissions have also decreased by around 30%. (Shecco, 2014)

2.4.2. Industry

NH_3 has a dominant position in the industry sector, although CO_2 has been implemented in cascade refrigeration systems in i.e. chemical plants and construction sites in Germany.

Surveys show also that CO_2 is expected to gain more ground and become a serious contender in the coming years. (Shecco, 2014)

2.4.3. City, Building & Transport

In Denmark and Germany, CO_2 has been implemented in the district heating systems of a few municipalities where carbon emissions have lowered substantially. Data centers have also implemented CO_2 cooling systems where lower costs have not only resulted from higher energy efficiencies, but also from space savings. (Shecco, 2014)

CO_2 heat pumps and refrigeration systems have been installed throughout Europe in various public & commercial buildings (hotels, hospitals, shopping centers etc.), and surveys predict that its market share will increase considerably. Heat pumps for residential space heating and domestic hot water production are also expected to become popular in Europe, by taking model from Japan where the technology covers 98% of the market share in private residential housing. (Shecco, 2014)

Mobile air conditioning in vehicles has been under investigation due to the EU Mobile Air Conditioning MAC directive, where developments in synthetic refrigerants still haven't satisfied the requirements. CO_2 is therefore still viewed by manufacturers as a possible solution for passenger cars. Implementations outside of EU have also been considered, since CO_2 refrigeration systems outperform current systems in over 95% of the driving conditions worldwide. Tests in Greece, India, and China have shown reductions in fuel consumption by over 25%. Further developments in CO_2 mobile air conditioning are currently underway and optimizations are also being made to electric vehicles, where COP values around 3 have been achieved. Surveys show though that the future for CO_2 systems in the mobile air conditioning market is still uncertain. As for now, there are some buses and trains in Germany and trucks in the Netherlands that use CO_2 in their respective air conditioning systems. (Shecco, 2014)

2.4.4. Sports

CO_2 systems have proven to become one of the most promising solutions in ice rink refrigeration. More than 20 ice rinks, mainly located in Europe, have applied CO_2 instead of brine in the secondary cycle. The main advantage with the switch to CO_2 is that the power consumption of the pumps in the distribution system reduces significantly, reaching values that are 90% smaller than what brine requires (Rogstam;Sawalha;& Nilsson, 2005). The first implementation of CO_2 in the secondary cycle was done in Austria in 1999, where NH_3 was used in the primary cycle. Similar technology was later installed in three ice rinks in Sweden, where NH_3 has had a dominant position in the primary cycle, therefore giving CO_2 considerable visibility on the market. (Shecco, 2014)

The first 100% CO_2-based system was implemented in the Marcel Dutil Arena, located in the Quebec province of Canada, in 2010. After installation the energy consumption was compared between the arena and similar ice rinks in the area with the same attendance rates. Results showed that the CO_2-based system generated 25% lower total energy costs than NH_3-based refrigeration systems, mainly due to the effective use of heat recovery which is possible with CO_2. (Simard, 2012) Due to its success, the same technology has since been implemented in several other rinks in Canada as well (Shecco, 2014).

After its renovations were completed in 2014, the ice rink in the small town of Gimo in Sweden became the first European ice rink to use a new energy management system based on transcritical CO_2 refrigeration. In order to utilize the heat recovery potential of CO_2 fully, the heat recovery system was designed and adapted to fit the properties of CO_2. A special feature of the ice rink was the implementation of a geothermal storage, further improving energy efficiency by allowing the sub-cooling of CO_2 during warm conditions and by utilizing the stored extra energy as a supplementary heat source during cold conditions. Reports after its first season of use showed that the energy consumption of the ice rink had shrunk by more than 50 percent, and that the operating cost now was about half compared to that of an another ice rink located in the same municipality that uses a traditional ammonia system. (Rogstam & Bolteau, 2015)

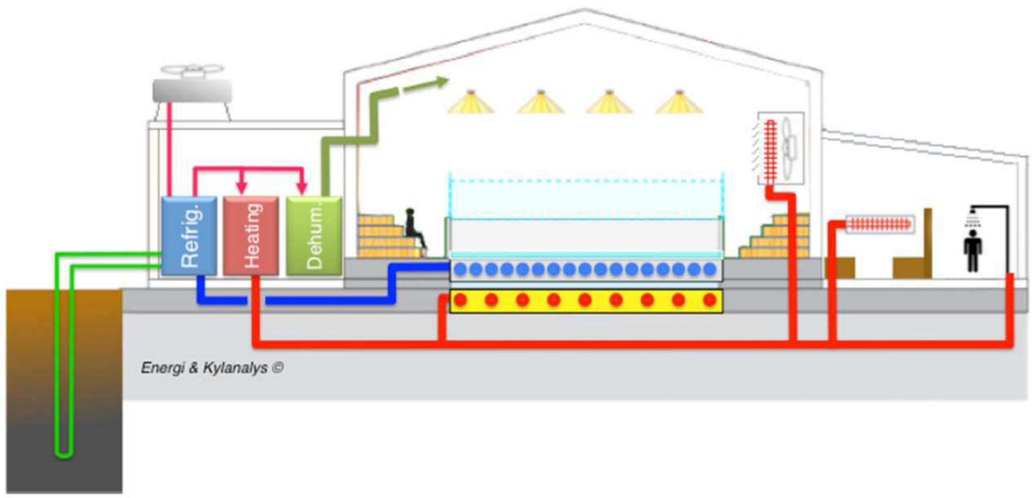

Figure 12: General energy system layout for Gimo ice rink. (Rogstam & Bolteau, 2015)

A large Canadian study was made public in 2013 that compared energy performance and life cycle cost between ice rink technologies used in the Quebec region of the country. The results showed that the 100% CO_2-based system was the most energy efficient with a global COP of 3,9 which includes heating. While its energy performance proved considerably better than that of conventional or NH_3-based refrigeration systems, its financial performance did not. The low operation cost was offset by a high investment cost that did not put the 100% CO_2-based technology in a favorable position. Instead an indirect CO_2-based system with brine as secondary fluid was calculated as the most economical, with much lower investment costs than 100% CO_2 due to lower material requirements in the distribution system and only a slight drop in estimated COP. The calculated annuity for the technology was 93600 $/year in local currency, while pure CO_2 technology was given an annuity of 124400 $/year. (CanmetENERGY, 2013)

High investment costs have so far proven to be the main drawback for CO_2 technology in ice rink applications. The initial costs as well as service expenditures are however expected to drop a lot mainly due to the ice rink and supermarket technology being very similar, which will bring competition from the latter to the former along with all the benefits. Stricter safety regulations for NH_3 bring further costs to ammonia-based systems, which is also advantageous for CO_2 when comparing the natural refrigerants. (Nguyen, 2012)

3. Ice rink operation

3.1. Energy demand

Ice rinks consume a lot of energy. Results from measurements done in Sweden, applicable to Finland due to similar conditions, indicate that the operation of an average ice rink requires about 1 GWh purchased energy per year. The energy distribution of a typical ice rink is illustrated in Figure 13, where it can be observed that the energy consumption is largely employed by the "big five" energy systems: refrigeration, heating, lighting, ventilation and dehumidification. (Rogstam;Beaini;& Hjert, 2014)

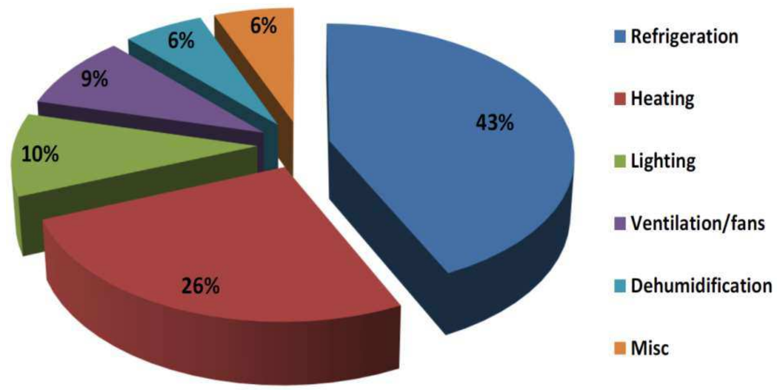

Figure 13: Energy distribution of an average ice rink. (Rogstam;Beaini;& Hjert, 2014)

Recommendations for improving operational performance are often related to one or several of the big five energy systems. An energy management system should be implemented as a first step though in order to monitor the energy consumption of the ice rink. This will enable the possibility to find potential sources of improvement among the big five, and will also allow for the documentation of results when modifications have been made. (Rogstam;Beaini;& Hjert, 2014)

3.1.1. Refrigeration

The ice rink refrigeration system is by far the largest energy consumer of the big five, covering more than 40% of the total energy demand. This is due to the great amount of conductive, convective, and radiant heat loads that together set the requirements for the refrigeration capacity. More than 80% of the loads are directed on the ice sheet, while the rest get absorbed by the distribution system (Karampour & Rogstam, 2012). The sources for the heat loads are illustrated in Figure 14. (ASHRAE, 2014)

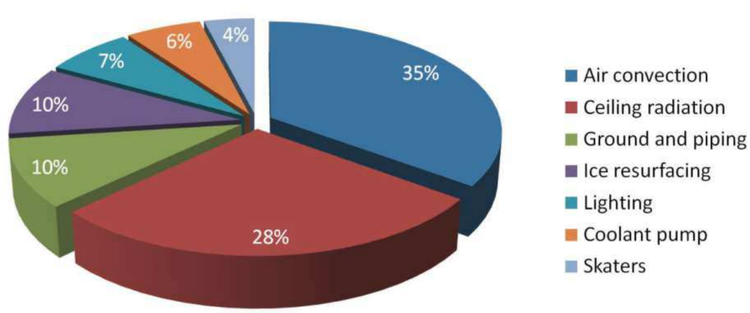

Figure 14: Typical heat loads on the refrigeration system. (Pachai, 2009)

As can be observed in Figure 14, air convection over the ice sheet results in the largest heat load on the refrigeration system. The heat load of the airflow is mainly covered by the air temperature followed by the relative humidity of the air in the large ice rink space, although sources show that the load can also be evenly split between the two at times (SaskPower, 2007). Improvements in space heating, air dehumidification, and ventilation can therefore reduce the heat load on the refrigeration system significantly, and as a result lower the demand for refrigeration energy. (ASHRAE, 2014)

The second largest heat load comes from ceiling radiation. Indoor ice rinks create a unique condition where a large cold plane, the ice sheet, is maintained beneath a large warm plane, the ceiling. With lighting radiant heat included, the total radiation heat load on the ice sheet equals or often even surpasses that of air convection. While typical improvements in lighting and space heating will reduce the radiation heat load, the greatest benefit is achieved by lowering the ceiling material's emissivity. (ASHRAE, 2014) A reduction of up to 80% on the ceiling radiation heat load is possible by placing a highly reflective paint or curtain at the ceiling surface. The low-e ceiling will also reflect light better which reduces the lighting demand and lowers the radiation heat load on the ice sheet even further. Consequently, surface temperatures of the ice sheet and the ceiling are more likely to stay optimal, resulting in good ice skating conditions and reductions in ceiling condensation. (SaskPower, 2007)

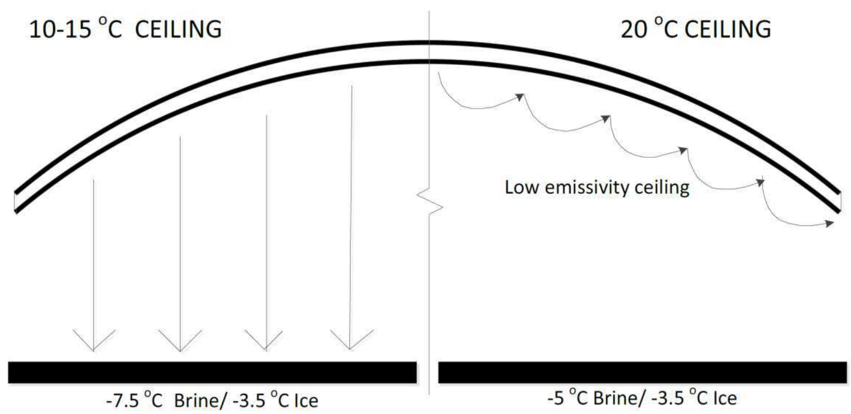

Figure 15: Effects of low emissivity ceiling. (Makhnatch, 2011)

Conductive heat loads from the ground and piping can be lowered with proper insulation. The insulation helps also minimize the spread of permafrost below the ice sheet, which if not controlled may lead to frost heaving with detrimental effects on both the rink and the piping. (Opetusministeriö, 2007) Conductive loads from above are mostly due to the ice resurfacing process, which usually makes use of warm water in the range of 30-60°C. The heat load from ice resurfacing can be reduced by lowering the floodwater volume and temperature, as long as it still results in good ice quality. (IIHF, 2002) Further benefits in both heat load reduction and ice quality can be achieved by switching to demineralized water, as pure water bonds very well with the existing ice sheet (SEDAC, 2011).

Further reductions in refrigeration demand due to heat loads can be achieved by making general adjustments to the ice sheet, without affecting its quality for ice skating. Raising its temperature during unoccupied periods will reduce its susceptibility to heat loads, which can bring large savings in refrigeration costs. Installing an infrared sensor for temperature control is therefore recommended. The total refrigeration demand can further be lowered by reducing the ice sheet thickness to 3 cm, which is a continuous process since ice tends to accumulate with use (IIHF, 2002). Refrigeration output is then optimized by resetting the refrigerant temperature throughout the day in order to match it with the ice thickness and the surface temperature requirements that vary with the activities taking place in the rink. (SEDAC, 2011)

As stated before, the refrigeration demand is a result of the heat loads on the refrigeration system. However, the amount of purchased energy used in order to fulfill the refrigeration demand depends on how energy efficient the design of the refrigeration system is, i.e. how high its COP is. Refrigeration systems are further investigated in section 3.2.

3.1.2. Heating

As shown in Figure 13, heating systems cover about a quarter of the average ice rink energy consumption. Heating is required for the following functions:

- **Space heating**. The goal in space heating is to maintain comfortable thermal conditions for the occupants. (IIHF, 2002) Finnish building code ranks the ice rink space as a half warm space, where indoor temperature is kept between 5°C and 17°C. The half warm ice rink space is furthermore connected to warm public spaces like dressing rooms, offices, and restaurants where indoor temperatures should be maintained at 20°C or above. Space heating is usually operated with a combination of air heating and either electric or water-based floor heating wherever possible, e.g. in the stands, making floor heating the base and heated air the tool for fine-tuning. Space heating may also be necessary in order to avoid structural damage, e.g. protection against frost heaving is enhanced by letting water run in pipes in the cold ground below the insulation of the ice sheet. (Opetusministeriö, 2007)
- **Snow melting**, if implemented. Snow is a waste product from ice resurfacing. (IIHF, 2002) The melting process is usually done by utilizing either the domestic water supply or the waste heat from the refrigeration process. (ASHRAE, 2014)
- **Hot water production**. Hot water is used for domestic purposes, e.g. showers, and for ice resurfacing. (IIHF, 2002)

Space heating requires by far most energy of the three. This is mainly due to the cooling effect of the ice sheet which is the cause for 75% of the total heating demand, as indicated in Figure 16. (Opetusministeriö, 2007) Space heating causes also heat loads on the ice sheet. Measures to reduce heating demand are therefore often focused on isolating the respective effects of ice rink space heating and ice sheet refrigeration from each other as much as possible. An important issue is to separate the air on the stands from the air over the ice sheet. Further measures to reduce heating are to lower the space temperatures during unoccupied periods and to only provide the spectator areas of the ice rink with heating when they're occupied. Improvements in refrigeration that reduce the ice sheet cooling effect will also lower the heating demand. (SEDAC, 2011)

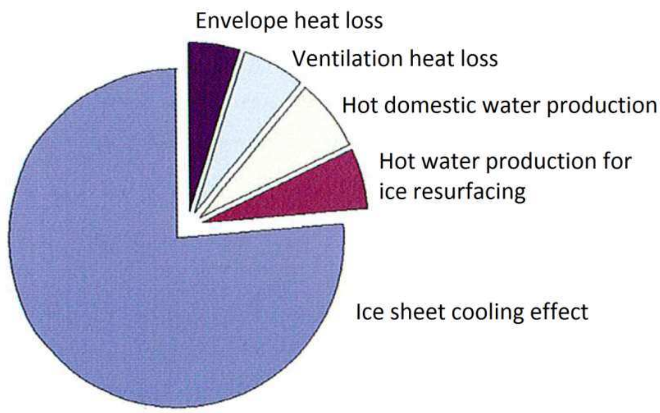

Figure 16: Distribution of ice rink heating demand. Translated from (Opetusministeriö, 2007)

While improvements in the heating energy system coupled with a properly insulated and airtight building envelope will minimize the heating demand, an even more important factor is the utilization of heat recovery from the refrigeration system. A waste heat recovery system can potentially cover the entire heating demand of an ice rink, if well implemented (IIHF, 2002). Heat recovery is further investigated in section 3.4. (Opetusministeriö, 2007)

3.1.3. Lighting

The majority of consumed lighting energy takes place in the ice rink space. Adjusting lighting levels according to type of activity on the ice, as illustrated in Table 3, will therefore bring the largest savings in lighting energy and also minimize the heat load on the ice sheet. It should however be noted that not only should the lighting fulfill the needs of the ice sheet occupants and the audience, in today's world it should also be sufficient for eventual TV-productions or live recordings (Rogstam;Beaini;& Hjert, 2014). Ice sheet specific lightning is turned off and general lighting only is used when the ice sheet is unoccupied or while it is being resurfaced. (Opetusministeriö, 2007)

ACTIVITY	FOOT-CANDLES
Pro Hockey	100
Amateur Hockey	50
Recreational Hockey	20
Figure Skating	15
Curling	10-20
Recreational Skating	10

Table 3: Recommended ice rink illumination levels. (SEDAC, 2011)

Further reductions in lighting energy can be achieved by taking the following measures:

- Installing LED-lights (Rogstam;Beaini;& Hjert, 2014)
- Reducing light intensity over the stands
- Installing occupancy sensors for areas with intermittent use

- Implementing a highly reflective ceiling to reduce lighting requirements (can be achieved with low-emissivity coating)

where the improvements will also reduce the heat load on the ice sheet. (SEDAC, 2011)

3.1.4. Ventilation

Ventilation provides the ice rink with fresh air in order to maintain space air quality, and that should ideally be its only purpose (SEDAC, 2011). It is often however closely linked to space heating and, depending on ambient climate conditions, also governed by dehumidification requirements. Mechanical ventilation is therefore the typical solution for an ice rink, usually equipping the facility with separate ventilation units for the two thermal zones in the building: the ice rink space and the public areas. (IIHF, 2002)

Air quality of an ice rink is affected by emissions from people, building materials, and the ice resurfacer if its machine runs on a combustion engine. Energy savings in ventilation can be achieved by implementing demand controlled fresh air intake, and by optimizing the airflow rates according to the needs for minimizing fan power. (IIHF, 2002) The former is usually achieved by installing sensors (CO_2, CO, and NO) that monitor air quality while the latter is solved by using variable frequency drives on the air handler motors. Switching to an electronic resurfacer will also reduce the requirements for fresh air intake in the ice rink space and therefore lower the ventilation energy demand even further. (SEDAC, 2011)

Improvements in heating and dehumidification can lower the ventilation demand, which may even further reduce the air convection heat load on the ice sheet. In order to make the improvements successful it is important that the building envelope and the structures that separate the thermal zones are airtight. This will increase controllability and reduce waste energy when making adjustments to heating or to dehumidification through ventilation. (Opetusministeriö, 2007)

3.1.5. Dehumidification

Excess moisture causes a higher relative humidity of the air, increasing the risk for corrosion and rot in structures. It also promotes the development of indoor air problems by enabling the growth of mold and fungus. Rink humidity is furthermore a contributor to the energy demand of the refrigeration system, as it potentially can cover up to 15% of the total heat load (SaskPower, 2007). While moisture loads in an ice rink can come from various sources, the biggest load by far comes from the outdoor air that enters the building via controlled ventilation and during warm and humid climate as uncontrolled infiltration leakage, where air with a high moisture load penetrates through openings and imperfections in the building envelope. (IIHF, 2002)

The dehumidification system of an ice rink is generally focused on minimizing the moisture load that comes with outdoor air. In practice this means that the intake of fresh air is reduced as much as possible, while still fulfilling the requirements for air quality during occupancy. (ASHRAE, 2014) Uncontrolled air infiltration is minimized by making the building envelope as airtight as possible, and by designing the entrances so that they remain sealed from the ice rink space even when the doors are open. Enclosed moisture within the ice rink space is then removed either by using mechanical dehumidification where the air is cooled below its dew point in order to condense the water vapor, or as a result of desiccant dehumidification where the air is passed over a material that absorbs water chemically well. (Opetusministeriö, 2007)

Figure 14 shows that dehumidification requires the least energy out of the big five systems, although conflicting results have appeared in recent studies where its share reaches 10-15% (Rogstam;Beaini;& Hjert, 2014). Summer operation is guaranteed to raise the dehumidification energy demand, since the higher water content in the outdoor air leads to a significant increase of the moisture load in the ice rink (Karampour & Rogstam, 2012). The following optimizations that lower dehumidification energy demand are nevertheless of great value:

- Dehumidifying fresh air separately from recirculated air, since the former usually has a much higher dew-point temperature
- Using mechanical dehumidification for high temperatures and moisture loads, while switching to desiccant humidification as they get lower (Opetusministeriö, 2007)
- Utilizing exhaust air heat recovery by the means of a desiccant wheel in order to preheat the make-up air
- Installing a low-e ceiling that reduces ceiling condensation by raising the surface temperature
- Dividing the ice sheet and stands into separate zones, as they have very distinctive dehumidification demands (Rogstam & Bolteau, 2015)

where the last action, illustrated in Figure 15, brings direct benefits to the refrigeration and lighting systems as well. (ASHRAE, 2014)

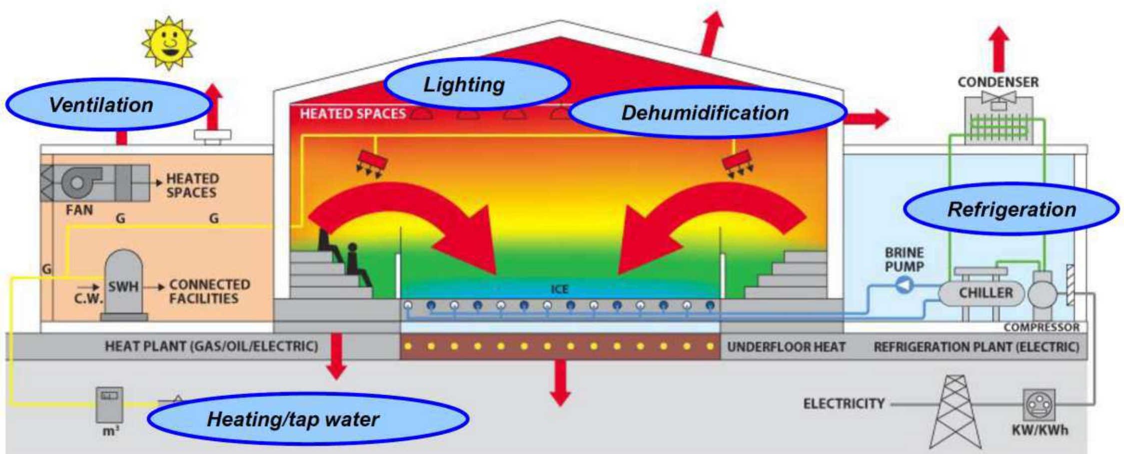

Figure 17: The big five energy systems of an ice rink. Modified from (Nguyen, 2012)

3.2. Refrigeration system

The refrigeration system is the heart of the ice rink. Almost all other energy systems of the building interact with the refrigeration process in the form of heat loads, which together set the dominant energy demand for refrigeration as illustrated in Figure 13. Apart from being the largest energy consumer, the system requires most of the time also the highest capital cost which can cover 60% of the total ice rink investment (Nguyen, 2012). The design of the refrigeration system is therefore critical and should in addition to energy usage and economics also consider operation, maintenance, safety, and environmental impact in the proposed solution. (IIHF, 2002)

The refrigeration system designs can roughly be divided into two groups: direct and indirect systems, where the indirect systems so far have been more commonly used in both Swedish and Finnish ice rinks. Both systems are described below and are later followed by Table 4 that summarizes their pros and cons.

3.2.1. Direct system

The direct system turns the rink piping into the evaporator of the refrigerant, as illustrated in Figure 18. This means that only one refrigerant runs through the whole system, requiring a huge charge of the chosen substance. The vapor that is formed in the rink piping is then sucked by compressors and fed into the condenser. Liquid refrigerant is pumped back into the rink after the condensation process. There is usually a large storage tank in between that sends and receives the refrigerant from the ice rink in order to provide for sudden escalations in the refrigeration energy demand. (Shahzad, 2006)

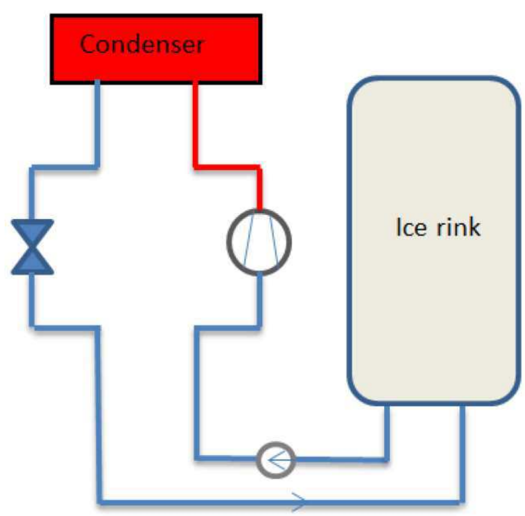

Figure 18: Direct refrigeration system of an ice rink. (Nguyen, 2012)

Safety regulations prevent certain hazardous refrigerants, e.g. NH_3 which had earlier been a popular choice, from being used in the direct system due to the risk of leaks close to human activity. Applications with R-22 are also diminishing as the synthetic refrigerant is being phased out due to its high global warming potential. (Nguyen, 2012) The direct system has therefore become less typical in ice rinks, resulting in that its design usually requires specialist help which further increases the already high capital costs of the system. This is a problem from the energy consumption perspective, considering that direct systems in general are more efficient than indirect systems. The wake of CO_2-applications can however increase the demand for direct systems in the future (Rogstam;Abdi;& Sawalha, 2014). (IIHF, 2002)

3.2.2. Indirect system

The main difference between the direct and the indirect system is that the latter uses a secondary cooling cycle in addition to the mechanical refrigeration unit, as shown in Figure 19. The primary refrigerant in the refrigeration unit cools down a secondary refrigerant in the evaporator. The secondary refrigerant is after the evaporator's heat exchange process pumped through the distribution system in a closed loop, where it circulates between the ice pad and the evaporator. Depending on refrigerant properties and safety regulations indirect systems can either be fully indirect, as illustrated in Figure 19, or partially indirect where there is no separate cycle between the condenser and the ambience. (Nguyen, 2012)

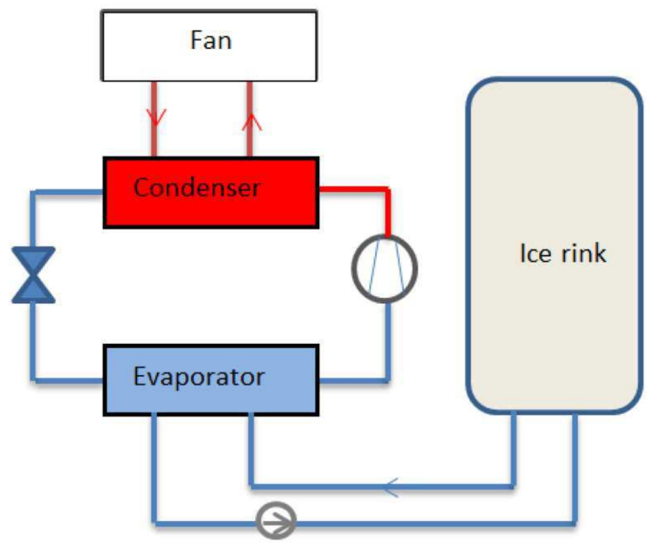

Figure 19: Indirect refrigeration system of an ice rink. (Nguyen, 2012)

The indirect system allows any refrigerant to be used in the mechanical refrigeration unit, since it won't come in close contact to human activity. NH_3 is often favored while the once popular R-22 has been disappearing from Finnish ice rinks due to its phase out. Brine, e.g. $CaCl_2$, has typically been chosen to run in the distribution system. (Nguyen, 2012)

The advantage of using the indirect system is that the required refrigerant amount is minimized and that the size of the refrigeration unit can be reduced while maintaining the same cooling capacity. This allows for the use of standard, factory made units which bring down capital cost (IIHF, 2002). The drawback with the indirect system is that its efficiency is generally lower than that of the direct system. This is due to the added heat exchanger, where the temperature differences between the primary and secondary refrigerants cause energy losses. Additional pumping power is also required for the circulation of the secondary refrigerant as shown in Figure 20, although this negative effect can be reduced significantly by installing a distribution system that is based on CO_2 or by replacing the brine that is running in the plastic pipes with ammonia water (Rogstam & Bolteau, 2015). (Nguyen, 2012)

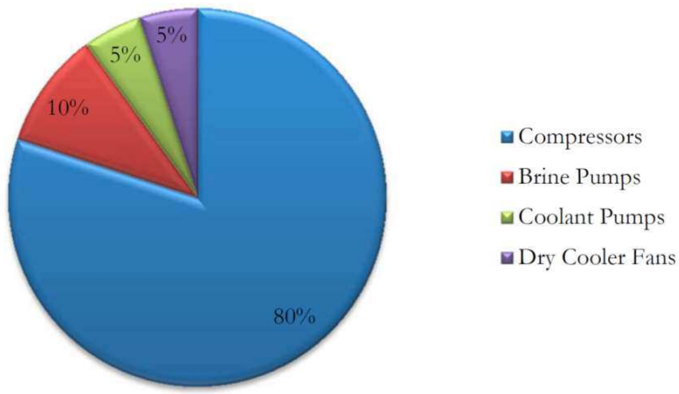

Figure 20: Average energy usage of an indirect ice rink refrigeration system. (Rogstam J. , 2010a)

Direct system	Indirect system
+ Energy efficiency + Simple	+ Use of factory made refrigeration units + Small refrigerant filling (environmentally positive) + Suitable to any refrigerant
- Not possible with certain refrigerants (ammonia) - Installation costs - Need of professional skills in design and in installing	- Lower energy efficiency than with direct system

Table 4: Features of direct and indirect refrigeration systems. (IIHF, 2002)

3.2.3. General refrigeration system enhancements

General enhancements of a refrigeration system can lower its energy consumption while still allowing it to fulfill the refrigeration demand caused by the heat loads on the system. Figure 20 shows that the greatest energy savings can be achieved in both direct and indirect systems through optimizations of the compressors, while improvements of the brine pumps in the indirect system are also of great worth.

A common problem with energy consuming brine pumps is that they operate at full speed for 24 hours a day. Furthermore, the consumed electricity by the pumps is converted to heat which has a warming effect on the brine, causing one of the smaller heat loads on the refrigeration system shown in Figure 14. In order to decrease energy consumption, variable speed pumps which can be controlled by brine temperature present a recommended solution. (Karampour M. , 2011)

Similar problems like those of brine pumps can also be found with compressors that run on constant speed instead of adapting to ice thickness, temperature, or occupancy. Electric motors equipped with frequency converters can be used in order to control the cooling capacity that should be provided. Having more than one compressor is also recommended for adjusting cooling capacity according to refrigeration demand, as additional compressors can run in parallel with the main compressor during sudden increases in the heat loads on the ice sheet. (Karampour M. , 2011)

3.3. Distribution system

Figure 21 shows a typical ice rink floor design. The main objective of the floor design from a thermodynamic perspective is to minimize the heat flow between the ground and the refrigeration process, primarily through proper insulation. This will diminish unnecessary heat loads on the distribution system and also help prevent the development of frost heaving. Embedding the cooling pipes in a concrete slab is the recommended solution, as it allows the ice rink to be used for other purposes as well. (Opetusministeriö, 2007)

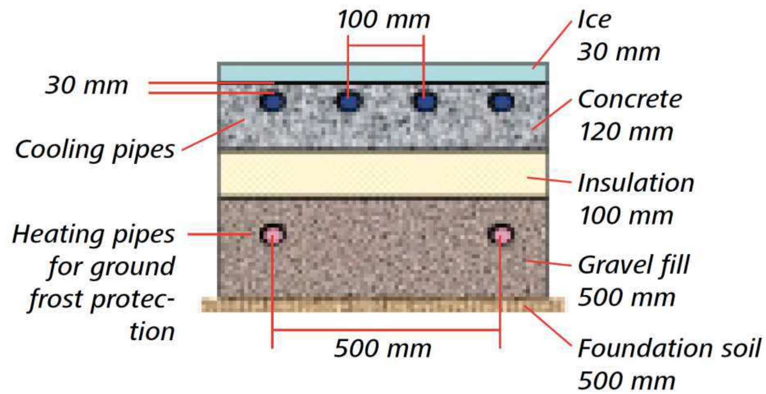

Figure 21: Typical ice rink floor design. (IIHF, 2002)

The cooling pipes are mounted quite near the surface of the concrete slab in order to minimize the resistance to heat transfer between the ice sheet and the piping. Typical depth is 20-30 mm. The rink pipes are laid in a U-shape with a mounting space of normally 75-125 mm, which is arranged either by binding the pipes directly to the concrete reinforcement or by using special rails. The rink piping is then connected to the distribution and collection mains, which are laid along the short side or the long side of the rink. Figure 22 illustrates the more favored arrangement where the mains, ideally represented by a design with reversed return headers, are located outside of the rink along the short side (Rogstam J. , 2010b). (IIHF, 2002)

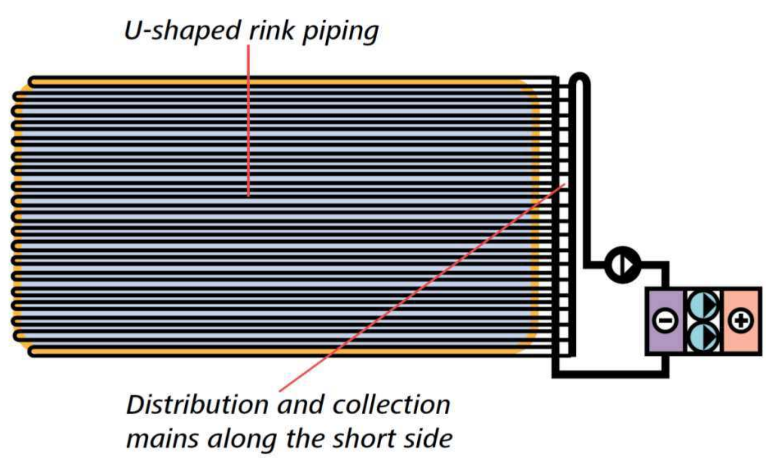

Figure 22: Typical piping arrangement in a distribution system. (IIHF, 2002)

There are generally three types of materials that are used for piping in the distribution system: plastic, steel, and copper. Plastic tubes are favored due to their low weight, easy installation, and low cost which together make the material the obvious choice for indirect systems where brine is used in the secondary cycle. Plastic can't however be used with CO_2 due to the high working pressure of the substance. Steel has therefore been viewed as the typical choice, although successful implementations with copper tubes have also been documented where the investment cost has been reduced as a result (Rogstam;Sawalha;& Nilsson, 2005). While both metals are more expensive than plastic pipes, they have the advantage that their heat transfer properties are superior which results in a higher energy efficiency and a lower operating cost of the distribution system. (Nguyen, 2012)

General improvements in the energy efficiency of the distribution system can be achieved by isolating the pipes from unnecessary heat loads as much as possible, and by minimizing the heat transfer resistance between the cooling pipes and the ice sheet. An action in the former category is to insulate the header pipes on the side of the rink in order to reduce the cooling losses before the refrigerant/brine enters the rink piping (Karampour M. , 2011). Another action belonging to the latter category is to install the cooling pipes above the concrete slab in an additional concrete layer that is more conductive. Results from simulations show a potential increase in the refrigeration system's COP by 3,5% when implementing an upper concrete layer with higher thermal conductivity. (Makhnatch, 2011)

3.4. Heat recovery

Figure 17 illustrates a traditional ice rink where the waste heat of the refrigeration system is rejected from the condenser into the atmosphere. Since the rejected heat is a byproduct of the refrigeration process, it can be viewed as free energy that potentially could cover the whole heating demand of the building (Opetusministeriö, 2007). Figure 23 highlights the logic of the heat recovery system where the waste heat replaces traditional energy sources, and only excess waste heat is rejected into the atmosphere from the condenser. The effective use of a heat recovery system plays a central role in the energy efficiency of an ice rink, as it potentially can reduce energy consumption and operating cost by over 40%. Furthermore, greenhouse gas emissions can be cut down by as much as 80% if the recovered heat replaces fossil fuels. (CanmetENERGY, 2013)

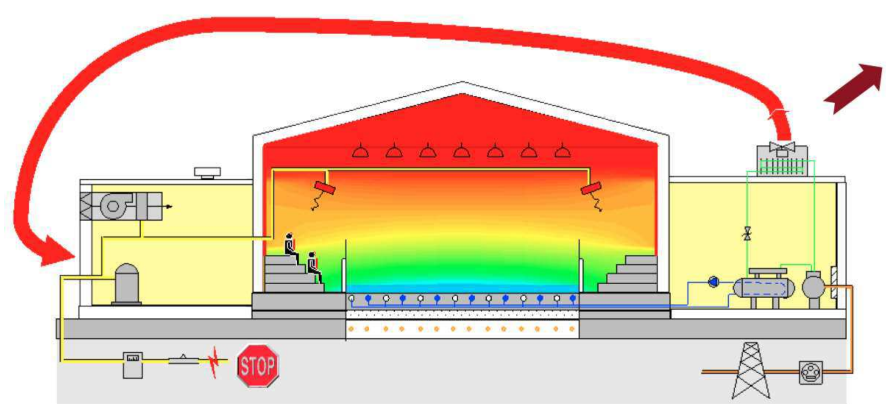

Figure 23: Logic of waste heat recovery in an ice rink. (CanmetENERGY, 2013)

Figure 24 shows the typical schematics for a heat recovery system that is connected to the refrigeration plant. The heat is distributed from the compressor to heat exchangers under different temperature levels. The highest temperature level, provided with refrigerant superheat, is reserved for domestic water heating while the lower levels are used for ground frost protection, floor heating, space heating, and dehumidification purposes. (Nguyen, 2012) Waste heat can also be used for the heating of resurfacing water and for snow melting. Normally there isn't enough superheat to cover the total heating demand of the tap water, resulting in the need for an additional high temperature energy source. (IIHF, 2002) However, a heat recovery system based on the transcritical operation of CO_2 in the refrigeration plant could increase the available superheat substantially. The elevated amount would minimize the need for additional energy sources, and by itself even cover the total heating demand at certain ambient temperatures. (Rogstam;Abdi;& Sawalha, 2014)

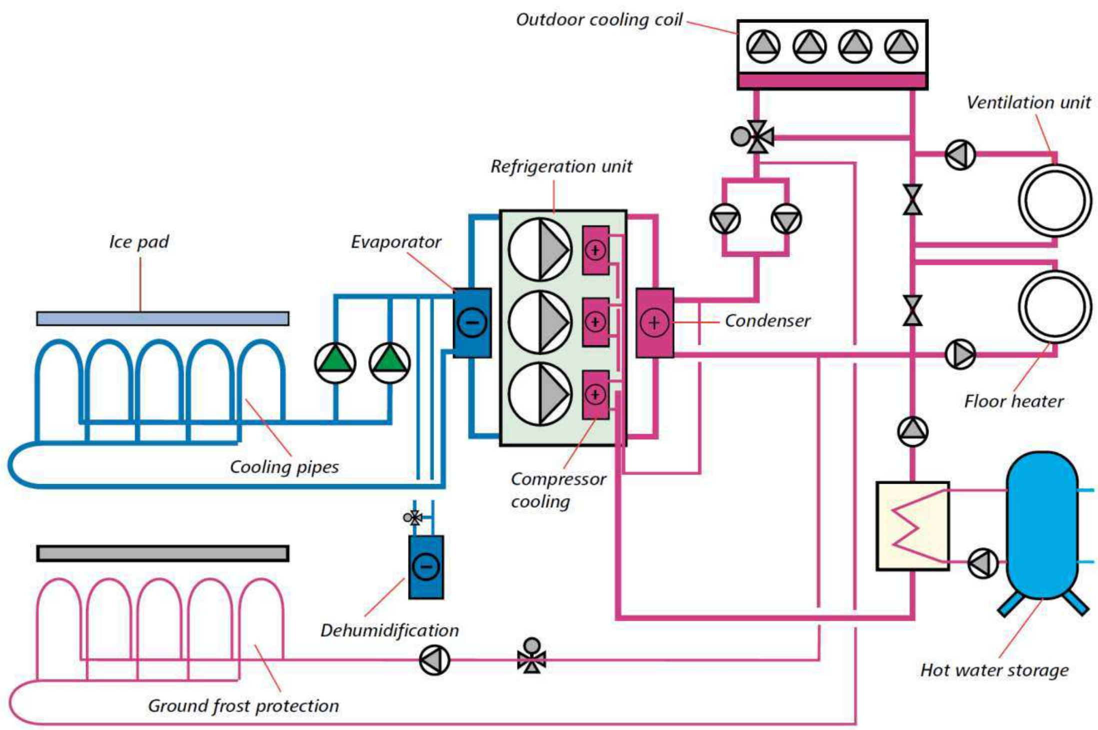

Figure 24: Refrigeration plant with heat recovery: heating of hot water, floor heating, and air heating. (IIHF, 2002)

The heat recovery concept can be further improved by adding a heat storage to the system. This allows excess waste heat to be stored and later used as supplemental heat in conditions where the heat recovered from the refrigeration system can't fulfill the heating demand. Heat storage designs include e.g. hot water tanks and phase change materials. (CanmetENERGY, 2013) The most energy efficient solution is to implement a geothermal storage, where excess waste heat is stored in boreholes which by demand provide a heat pump with heat at optimal temperature levels. Figure 25 illustrates the concept of a geothermal storage, where the upper half shows the loading mechanism and the lower half shows extraction mechanism. (Rogstam;Beaini;& Hjert, 2014)

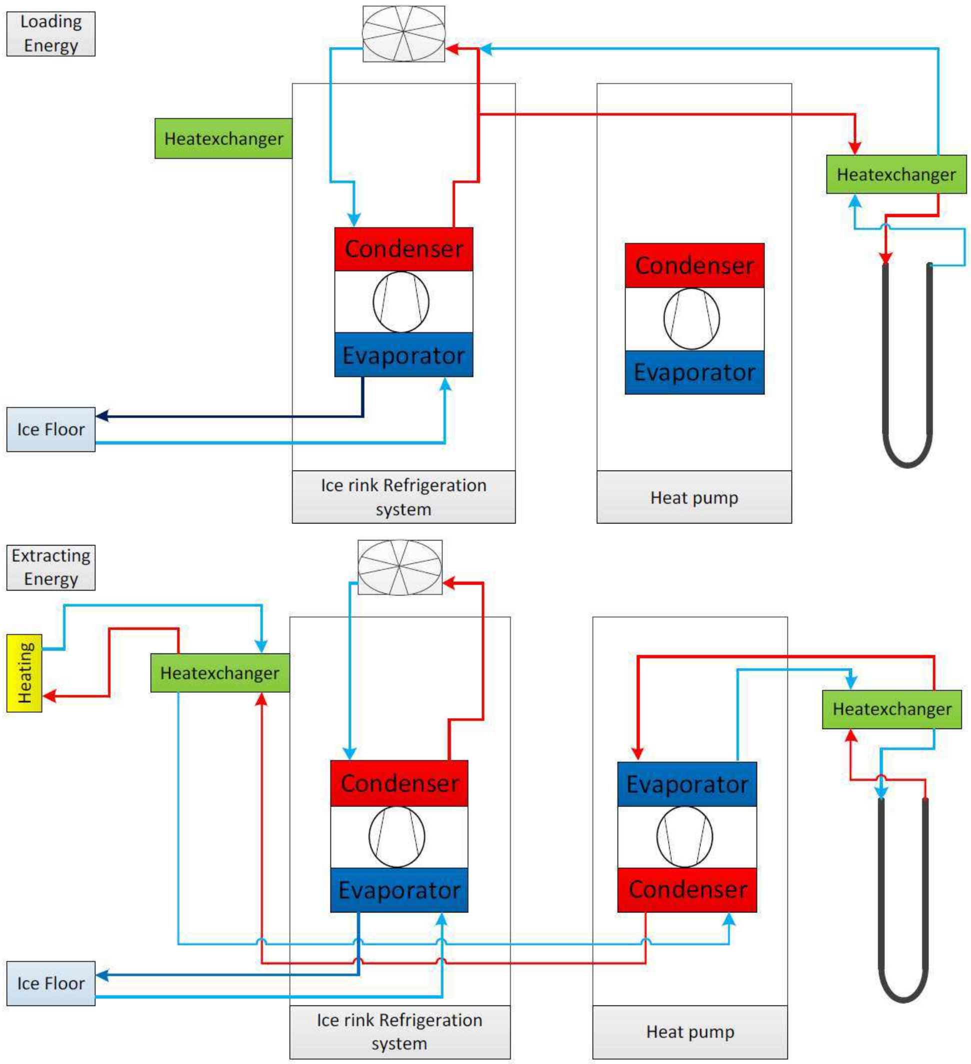

Figure 25: Geothermal storage concept. (Rogstam;Beaini;& Hjert, 2014)

4. Life-cycle cost analysis methodology

4.1. Principle of LCC analysis

The life-cycle cost (LCC) analysis methodology takes a holistic approach when comparing the economic performance between technical solutions, which in this case are refrigeration systems. All costs connected to a refrigeration system are collected over a timeframe which extends from the implementation of the system until its planned ownership ends. The costs are then discounted to their present values and summed together with the investment cost in order to produce the life-cycle cost of the system. The life-cycle cost indicates how much the total cost of ownership for a system is in a single present value, which makes it an effective tool when comparing the economic performance between different technical solutions. (ASHRAE, 2015)

The application of the LCC methodology brings beneficial opportunities both to the supplier and the user. Contractors and consultants can put their focus on maximizing the quality of the system solution instead of minimizing investment costs, while users are motivated to continuously improve the performance and processes of the system after its implementation. The operating costs and service costs are therefore usually much lower in system solutions based on the LCC methodology, which eventually will result in large savings despite a possibly larger investment cost. (Laitinen;Nykänen;& Paiho, 2010)

4.1.1. Present value formula and the discount rate

Future costs in LCC calculations are discounted to their corresponding present values and summed by applying Equation 4:

$$PV = \sum_{n=0}^{N} \frac{C_n}{(1+r)^n}$$

Equation 4: Present value formula. (Berk & DeMarzo, 2011)

where C_n is the future cost that occurs during time period n within the total life cycle length N, and r is the discount rate for the time period which takes into account the time value of money and the uncertainty of future cash flows.

The time value of money states that costs at the present time are of higher value than equally large costs in the future. This is due to the potential earning capacity of money available. Costs will however reduce the money available, and losses in potential earnings have a bigger impact on LCC calculation results the earlier they occur.

The uncertainty of future cash flows acknowledges the unpredictability of certain input data, e.g. future development of inflation or price level. It is therefore required that a risk premium set by the buyer is included in the calculation of the discount rate. This is usually done by considering the required returns in order to maintain the capital structure of the buyer, the cost of capital, or by comparing the investment with similar projects. (Berk & DeMarzo, 2011)

4.2. Input data in LCC analysis

4.2.1. Investment

The investment cost covers the procurement and installation of a refrigeration system. The investment marks the starting point of a system life-cycle, which means that its cost components readily are at their present values and won't be discounted in LCC calculations. Reasonable estimations can be gathered from recent installations of comparable design or from suppliers and other experts in the field. (ASHRAE, 2015)

Investment costs in a life-cycle cost analysis are usually compiled from a comparative perspective. This means that there are some elements that are treated as sunk costs and won't be included when comparing investment opportunities. Sunk costs are costs that have been or will be paid regardless of which system is chosen: in the case of an ice rink it could be the machine room or a pre-existing distribution system that possibly could be reused. (Berk & DeMarzo, 2011)

4.2.2. Operating cost

The performance of a refrigeration system during its life cycle is estimated by making energy consumption calculations that also take into account local conditions. The operating cost is then determined by coupling the estimated energy consumption with the unit cost of energy, where the latter depends on the energy source used and the future economic outlook. Operating costs over the system life cycle are discounted to their present values by using Equation 4.

It should be noted that more accurate results for operating cost can be achieved when calculations are made on a more detailed level since unit costs for energy can vary greatly with consumption levels, time of day, and time of year. (ASHRAE, 2015)

4.2.3. Service cost

The service cost for a refrigeration system depends on various factors:

- **System type.** Different refrigeration systems have different requirements in terms of component specifications and general safety, resulting in system solutions where the service costs vary.
- **System run time.** The duration of system operation affects maintenance cost, where the number of hours often dictate some tasks.
- **Equipment age.** Technologies in equipment design and application change with time, which affects service costs. System errors also tend to increase with age.
- **Geographical location.** Local climate and infrastructure can have varying effects on refrigeration systems, which may affect service cost. Accessibility to service provider is also an important factor, as long distances can raise costs.

Service costs are usually subdivided to groups depending on the frequency and scale of service actions (CanmetENERGY, 2013). Regular maintenance and repairs that happen yearly are discounted to their present values by using Equation 4, while periodic service actions that occur less frequently and usually are of much higher cost are discounted to their present values by only including their relevant time periods in Equation 4. (ASHRAE, 2015)

4.2.4. Residual value

Some of the equipment in a refrigeration system might have a different economic lifespan than the system itself, resulting in the equipment or asset having a residual value at the end of the system life-cycle. The residual value for an asset is calculated by using Equation 5:

$$Residual\ value = Investment\ \frac{Remaining\ economic\ lifespan\ of\ asset}{Total\ economic\ lifespan\ of\ asset}$$

Equation 5: Residual value formula. (Laitinen;Nykänen;& Paiho, 2010)

which indicates that the depreciation is usually linear in LCC calculations. While residual values are viewed as the opposite of costs, the calculations of their respective present values are done by using the same principles as Equation 4. (CanmetENERGY, 2013)

4.3. LCC analysis tools

4.3.1. Present value method

The present value method puts together the present worth of all input costs and values that occur during the life-cycle of a system, resulting in what is called the total life-cycle cost. The calculations are done by applying Equation 6:

$$LCC = I_{pv} + O_{pv} + YS_{pv} + PS_{pv} - R_{pv}$$

Equation 6: Total life-cycle cost formula. (Laitinen;Nykänen;& Paiho, 2010)

where the investment I_{pv}, operating cost O_{pv}, yearly service cost YS_{pv}, periodic service cost PS_{pv}, and residual value R_{pv} are all expressed in their respective present values.

In a comparative LCC analysis, the system that has the lowest total life-cycle cost is the preferred option. This applies however only for cases where the compared systems have an economic lifespan of equal length, as higher life-cycle costs might simply be due to a longer lifespan and not because of a disadvantage in cost effectiveness. (Berk & DeMarzo, 2011)

4.3.2. Equivalent annual cost method

The equivalent annual cost method recalculates the present values of the input data into equivalent annuities by using Equation 7:

$$EAC = \frac{PV}{\frac{1}{r}\left(1 - \frac{1}{(1+r)^N}\right)}$$

Equation 7: Equivalent annual cost formula. (Berk & DeMarzo, 2011)

where r is the discount rate and N is the total life cycle length. The equivalent annuities are then summed in the same fashion as indicated in Equation 6 in order to give the total equivalent annual cost of a system during its economic lifespan.

Also called total annuity, the equivalent annual cost gives an understanding of how expensive a system is per year from a comparative perspective. Options with different economic lifespans can therefore be compared, making this method preferable over the present value method in such cases. The options must however be of equal risk in order to be compared, since comparable results require the same discount rate to be used for all calculations. (Berk & DeMarzo, 2011)

4.3.3. Payback method

The payback method calculates the period of time required to recover the cost of an investment. In the context of LCC analysis, the payback period represents the amount of time it takes for an economic option to have a lower cumulative cost in comparison to its alternative. Decision makers may have set requirements on maximum time allowed, which means that the most economic option may be rejected if the payback period isn't shorter than the prespecified length of time.

While the payback method is very straightforward in comparison to other tools, it does however have some pitfalls: it ignores the time value of money, it relies on subjective opinion regarding maximum period length, and it downplays the yearly benefits of an option that ultimately would make it the most profitable option after the payback period. The payback method is therefore not recommended to be used by itself, but rather as supportive method in LCC analysis. (Berk & DeMarzo, 2011)

4.3.4. Sensitivity and scenario analysis

The input data in LCC calculations are often based on estimations which may lead to inaccurate results. This is typically due to the estimations being derived from sparse data or unpredictable factors such as the future developments in price level and inflation. A sensitivity analysis determines how variations in input data and their future escalations affect the results, and consequently gives an understanding of how reliable the conclusions drawn in the LCC analysis can be. Moreover, the tool indicates which parameters are the most important and may require further investigation in order to generate decisive results.

A sensitivity analysis investigates the effects of a single parameter on the calculated results. In reality, certain factors may affect more than one parameter. Scenario analysis investigates the effect on LCC results when changing multiple parameters, usually by creating best and worst case scenarios. (Berk & DeMarzo, 2011)

5. Case ice rink in Sweden

5.1. Case presentation

A municipality in Sweden had reacted to the increasing operating and service costs of the current refrigeration system in its ice rink and wanted to investigate possible benefits of installing a new system. The current state of the ice rink was reviewed in April 2016 and new solutions were suggested. Developed LCC models were then applied to the case context in order to evaluate the economic performance of the current system and the potential candidates for replacement, where the costs of each system's solution to fulfill the heating demand of the ice rink were also taken into account.

5.2. Current state of case ice rink

5.2.1. Facility

The ice rink was built in 1978 and its size represents that of a typical ice rink in Sweden and Finland which can be used for practice or competition. The season starts in mid-August and ends in March. The building envelope is insulated and covered with sheet metal. Inside the walls are covered with wood panels while acoustical sound panels hang from the sheet metal roof. The temperature in the ice rink is 8-9 °C.

The current refrigeration system is a traditional ammonia-based indirect system that was installed in 1991 in a building next to the ice rink. Calcium chloride functions as the secondary refrigerant that runs through the distribution system made of plastic pipes embedded in concrete below the ice sheet. There is no modern energy management system in use, which means that compressors and pumps are not capacity regulated and can therefore only run at full power when turned on.

Figure 26: Current NH_3-based refrigeration system operating in the case ice rink.

Space heating is done via ventilation and water based heating systems. District heating is the main heat source, while some heat is also recovered from the refrigeration system. The heat recovery is however done only through a hot gas heat exchanger, meaning that max 10% of available condensation heat is being utilized. Furthermore, the absence of capacity regulation in the refrigeration system will make compressors stand still for large periods of time during which no heat can be recovered.

The ventilation and dehumidification functions are combined and share the same distribution canals that are directed towards the ice sheet, resulting in misplaced space heating and unnecessary heat loads on the refrigeration system. The LED lighting system had recently been installed and is performing well.

The ice pad lacks frost protection and minor elevations of the concrete floor can be found. The condition of the ice pad is nevertheless deemed acceptable for reuse in new refrigeration system solutions. A new machine room is recommended for new system solutions since the one currently in use is challenging to reach due to an obstructing bridge structure, while the floor of the space itself is located below ground level which would make installation even more difficult.

5.2.2. Energy consumption

The ice rink consumes around 1000 MWh energy on a yearly basis, which is the average for typical ice rinks. Circa 600 MWh is consumed as electricity, although how it is divided between the big five energy systems can't be specified for certain as there is no measurement beyond total consumption per month. A small decline in electricity consumption can be observed in 2015 due to the new LED lighting system, while the district heating consumption has risen from 330 MWh to 450 MWh mainly due to increased demand in thermal comfort.

Year	Electricity (MWh)	District heating (MWh)	Total (MWh)
2012	599	331	930
2013	607	366	973
2014	627	331	958
2015	588	451	1039

Table 5: Energy consumption per year in case ice rink.

5.2.3. General recommendations

Based on the review of its current condition, general recommendations for the case ice rink were given as follows:

- **Refrigeration system**
  - Investigate benefits of a new refrigeration system
  - Optimize heat recovery from the refrigeration process
- **Heating**
  - Maximize the use of recovered heat
  - Accumulate for spikes in demand

    - Investigate benefits of potential heat export
- **Ventilation**
    - Separate ventilation from dehumidification
    - Let ventilated air be distributed over the stands
    - Maintain temperature levels by demand
    - Optimize airflow rates through capacity regulation of fans
- **Dehumidification**
    - Let dehumidified air be distributed over the ice sheet
    - Switch to a new dehumidifier that can make use of recovered heat
- **Lighting**
    - Adjust light levels according to demand
- **Ice pad**
    - Measure the elevations on the concrete floor and even them out where necessary
- **Machine room**
    - Prepare for new machine room in case of new refrigeration system

5.3. New refrigeration system solutions for case ice rink

Based on the reviewed condition of the case ice rink, three alternative solutions for a new refrigeration system were suggested. The presented solutions, including their variations, cover the refrigeration and heating demand of the ice rink.

5.3.1. CO_2 direct

The CO_2 direct system uses carbon dioxide in the whole system, which is preferable since the substance requires very little pumping power in order to flow under the ice. Furthermore, a direct system eliminates the need for a heat exchanger to the distribution system adding even more efficiency to the system solution.

Figure 27: CO_2 direct refrigeration system.

The drawback with the CO_2 direct system in this context is that it requires additional investment in a new distribution system made of copper pipes embedded in a concrete layer above the existing ice pad. This is because the plastic pipes currently in use can't handle the pressure of CO_2 in operation.

A state of the art heat recovery system is included in the system solution that will eliminate the need for an external heat source during the season. District heating will cover the heat demand during off season.

5.3.2. CO_2 indirect

The CO_2 indirect system is a partially indirect system solution that makes use of a secondary refrigerant in the distribution cycle. In this case context it will save investment costs since the existing plastic pipes can be reused in the system solution. The drawback is that the indirect system has a lower energy efficiency compared to a direct system, although having ammonia-water flow under the ice will minimize the difference due to its low pumping power.

A state of the art heat recovery system is also included in the CO_2 indirect system solution that will eliminate the need for an external heat source during the season. District heating will cover the heat demand during off season.

Figure 28: CO_2 indirect refrigeration system.

5.3.3. NH_3 indirect

The NH_3 indirect system is a modern version of the refrigeration system currently in operation in the case ice rink. This traditional fully indirect system comes with some added benefits in the newer version: smaller charges (below 50kg), higher efficiencies, good capacity regulation, and more reliability.

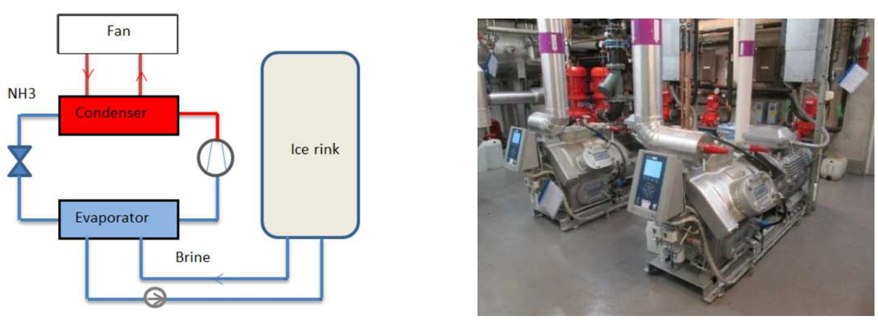

Figure 29: NH_3 indirect refrigeration system.

A fully indirect system creates losses in energy efficiency due to added heat exchangers and higher energy consumption of auxiliary components. NH_3 has nevertheless in terms of refrigeration a higher COP than CO_2, which makes it a popular option.

Heat recovery from NH_3 indirect systems can't cover the entire heat demand of an ice rink and must therefore be accompanied by an external heat source. Two variations of the system solution have therefore been suggested, where the first one makes use of the existing district heating system and the second one includes a heat pump that is in operation during the season. District heating will cover the heat demand during off season in each case.

5.4. Additional options

5.4.1. Heat recovery

A modern ice rink refrigeration system is assumed to include heat recovery due to the benefits the inclusion brings to energy efficiency and operating cost of heating. The system solutions presented above all describe their respective heat recovery and general heating strategies, which as observed mainly depend on the chosen refrigerant.

Both the CO_2 direct and indirect solutions can recover sufficient heat at high temperatures from their refrigeration systems in order to cover the whole heating demand of the ice rink. The recovered heat is then distributed to the heating systems of the ice rink according to the waterfall principle, where heat is extracted at the necessary temperature level of each heating demand.

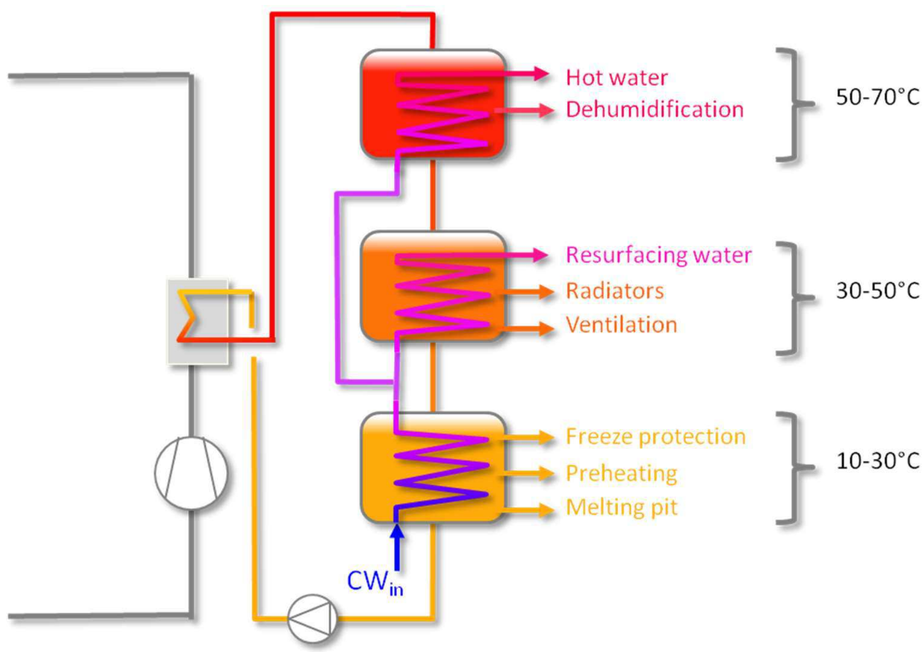

Figure 30: Heat recovery system based on waterfall principle.

The NH_3 indirect solution by itself can't recover sufficient heat at high temperatures in order to cover the heating demand of the rink. The temperature of the heat can however be raised to necessary levels if a heat pump function is connected to the warm side of the refrigeration process. From an energy consumption perspective this is a favorable solution, but it comes however at the expense of further investment costs.

5.4.2. Heat export

Rarely does an ice rink consume all the heating energy, usually between 800 and 1200 MWH, that is released from the refrigeration system. The possibility to export heat to nearby facilities is therefore an option worthy of exploring. The exported heat must however fulfill the temperature level demand of recipient buildings in order to be useful in their heating systems.

The CO_2 direct and indirect systems have both the capability of exporting excess heat at enough high temperature levels to nearby facilities. In the best case scenario all excess heat would be exported to a building with a high heating demand, e.g. a swimming hall. In this case context however, the distance to the swimming hall in the municipality is quite long making it not a viable option for the time being. Variations of the CO_2 direct and indirect solutions have been presented where some of the excess heat is exported to the locker rooms of a sports ground that is located next to the ice rink.

The excess heat of the NH_3 indirect system has too low a temperature level to be exported to nearby facilities. The variation of the system solution that includes a heat pump function could potentially export excess heat, but only if the heat pump is designed for a heating demand beyond that of the ice rink itself. Heat export is therefore not included as an option in the NH_3 indirect system.

5.4.3. Geothermal storage

A geothermal storage benefits the ice rink in two ways: it enables subcooling of the refrigeration process during warmer periods which makes the system solution more energy efficient, and it can store excess heat to be used later when necessary. The latter is especially useful in the case of heat export, and it can also eliminate the need for an external heat source during off season when the refrigeration system is not in operation.

In this case context, the possible benefits of implementing a geothermal storage are for now not further investigated. While the option probably would lead to operational savings during off season, the municipality has chosen to let the district heating cover the heating demand during the summer months for the time being.

6. LCC analysis of case ice rink

6.1. LCC analysis model presentation

A life-cycle cost analysis model was developed in order to allow for efficient investigation of refrigeration system performance in ice rinks. The model was created in Excel and makes use of programmed macro commands together with linked input data, therefore aiming to enhance the user experience. A finalized version of the model was put into use in the context of comparative LCC analysis of refrigeration systems in the case ice rink.

The LCC model goes through the following steps when analyzing refrigeration system performance:

- Input of base data
- Input of component data
- Input of operational data
- Setting up the systems to be analyzed
- Analyzing and comparing system performance

6.1.1. Input of base data

Base data includes basic information about the case ice rink and general input data such as refrigeration demand, heating demand, and energy source cost where all are used in the performance calculations for the systems that are to be compared. The input data represent a typical year of operation in the case context and are entered in monthly values, allowing for a more realistic analysis as demands and unit costs may fluctuate significantly from a certain time of year to another. Energy source costs are further divided into unit costs and fixed costs, as some energy sources like district heating can have fixed costs per year that are of a considerable amount.

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Electricity													
Price/MWh	SEK												
Fixed price	SEK												
District heating													
Price/MWh	SEK												
Fixed price	SEK												

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Heat export													
Price/MWh	SEK												
Fixed price	SEK												

Figure 31: Energy source costs in base data input.

If there is a nearby facility that could be a potential recipient of heat export its case may be documented, where the heat export prices are expressed in the same manner as energy source costs with monthly unit and fixed costs. If the recipient building and the ice rink should have the same owner, the heat export price is to be expressed as the energy source cost of the recipient building. The cost savings in purchased energy for heating in the recipient building are that way taken into account in the LCC calculations of the ice rink refrigeration system.

6.1.2. Input of component data

Component data refers to system or component information and costs, where the latter are used directly in the LCC calculations. Data input for the refrigeration system can be done either at a module level for each cycle or at the more detailed component level, providing further information on cost allocation. Input of data for heat recovery systems or external heating sources is done at the module level.

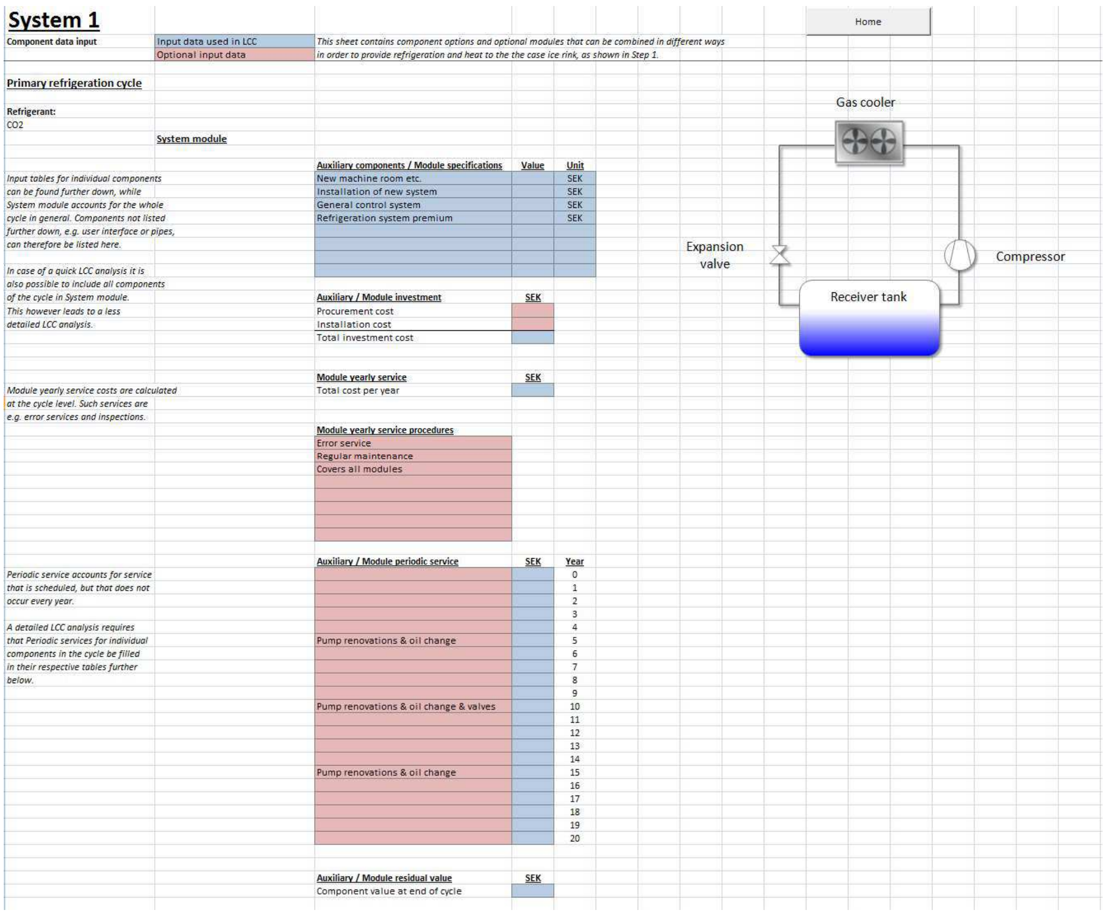

Figure 32: Component data input of a module.

Investment data can be broken down into documented cost components when desired, where procurement and installation cost are the most typical. The sum of all cost components result in the total investment cost that is linked to the LCC calculations.

Service costs are grouped into yearly and periodic costs. Yearly service consists of error service and regular maintenance that generate an estimated total cost each year which is linked to the LCC calculations. Service procedures and their respective costs can be documented in order to make detailed information available.

Periodic service consists of service procedures that are not performed each year, but usually create spikes in service costs on when they occur. The frequency of such service procedures are outlined in the system life cycle, where their corresponding sums are linked to the LCC calculations.

If a system component has a residual value at the end of the system life cycle, its amount can be added to the input data. The value is linked the LCC calculations where it will lower the total life-cycle cost of the system.

6.1.3. Input of operational data

The technical performance of a system solution is calculated for a typical year of operation, where the refrigeration and heating demands of the ice rink take into account local conditions and climate. The calculations are done outside the model by applying appropriate methods. Results are then inserted into a table in the model that is linked to the LCC calculations, where energy costs are calculated. There are many possible variations of a refrigeration system, especially regarding the chosen heating strategy. The variations are called setups in the model, and each setup has its own table. Figure 33 shows the base setup table, from which the various setup tables are constructed by removing the rows that are not relevant for the system setup, e.g. if district heating is not included then its row is removed.

Base setup table	All modules showing		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yearly total
Refrigeration system energy consumption															
	All sectors														
	MWh electricity	Total consumption													
	Per sector														
	MWh electricity	Refrigeration													
		Heat recovery													
		Geothermal													
		Heat export													
External systems energy consumption			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yearly total
	External heat source														
	MWh electricity	Heat pump													
	MWh heat	District heating													
	MWh electricity	Electric heating													
General performance indicators			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yearly total
	Energy consumption														
	MWh	Total													
		Refrigeration													
		Heating													
	COP														
		Global													
		Refrigeration													
		Heating													
	Heat recovered														
	MWh	Total													
Heat export			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yearly total
	Heat export														
	MWh	*Energy saved/transferred*													

Figure 33: Base setup table used in operational data input.

The operational input data are expressed at monthly values. This allows for a more realistic analysis, since the respective fluctuations of energy consumption and unit energy cost can have a significant impact on the total energy cost for a year of operation. The input of data can be done at a general level by filling the blue cells indicated in Figure 33, which are the linked cells used in the LCC calculations. Although the end results of the LCC analysis will remain the same, filling the red cells will lead to calculations that can show the system performance on a more detailed level when requested.

In a system setup that applies heat export, how its row is filled depends on the ownership of the client facility. If it's the same owner as the ice rink, the values filled should represent the decrease in purchased energy used for heating in the recipient building. If the owner is not the same, the filled values should indicate the amount of energy transferred to the client. The filled values are linked to the LCC calculations where they are multiplied with their export price counterparts from the base data input, resulting in earnings that will have a lowering effect on the total life-cycle cost of the system.

6.1.4. Setting up the systems to be analyzed

In this step a system solution is chosen to be analyzed. Relevant component and operational data are linked to the LCC calculations, and a summary displays the chosen system structure along with its performance. Modifications can be made by selecting a heating strategy to fulfill the demand of the heating systems, which will enable relevant input data and exclude data for other heating strategies. This is done by clicking on the desired heating strategy button which automatically restructures the system and updates the LCC calculations, resulting in new evaluations of the system overall performance. In the model it is also possible to quickly simulate how different pipe materials in the distribution system or the application of a thermal concrete layer can affect system performance, if such information is demanded in a case investigation.

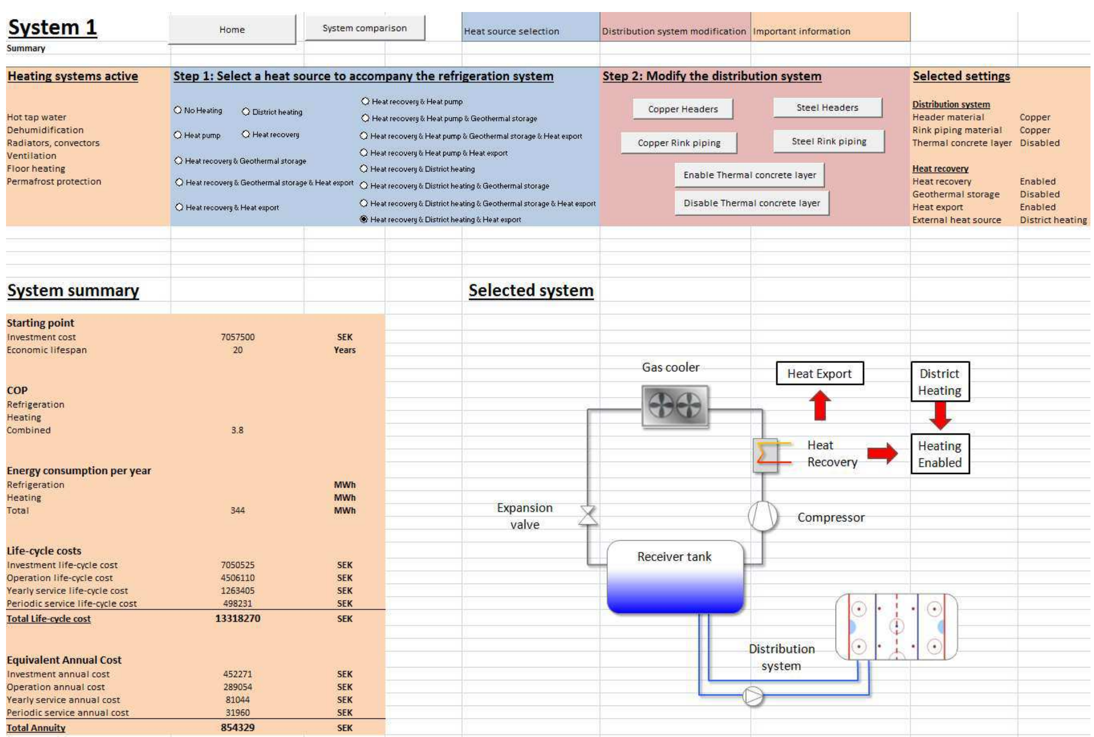

Figure 34: System selection.

6.1.5. Analyzing and comparing system performance

This stage tests the financial performance of systems that were set up in the previous step by conducting a sensitivity and scenario analysis. Input values and their future escalations for all systems can be modified, while the results in their respective LCC calculations are updated immediately. The financial performance of each system in various economic scenarios can therefore effectively be analyzed. The charts seen in Figure 35 illustrate the calculated results of the various LCC analysis methods used in the model to evaluate system financial performance.

Figure 35: Analysis and comparison of system performance.

The model can conduct a sensitivity and scenario analysis on three system solutions simultaneously. Results from the analysis can then be extracted to a separate excel sheet where a final comparison between all candidates is performed.

6.2. *Input data*

Table 6 lists the system solutions presented in sections 5.3 and 5.4 that are analyzed in this case context along with their specifications. The economic lifespan of each system is set to 20 years, which is a valid assumption for the new candidates. The existing system is more likely to have a shorter lifespan, which is factor that needs to be addressed when applying the tools of LCC analysis later in the case investigation.

System solution specifications

	A	B	C	D	E	F	G
System setup and economic lifespan in years							
Existing system	20?						
CO2 Direct & district heating		20					
CO2 Indirect & district heating			20				
CO2 Direct & district heating & heat export				20			
CO2 Indirect &district heating & heat export					20		
NH3 indirect & district heating						20	
NH3 indirect & heat pump & district heating							20
Investments required							
Machine room		X	X	X	X	X	X
Refrigeration system CO2 direct		X		X			
Refrigeration system CO2 indirect			X		X		
Refrigeration system NH3 indirect						X	X
Heat recovery system - standalone		X	X	X	X		
Heat recovery system - supplemental						X	X
Heat pump							X
Distribution system (pipes + concrete)		X		X			
Energy management system		X	X	X	X	X	X
Geothermal storage							
Heat export to nearby locker rooms				X	X		
Existing - no investments required							
Machine room	X						
Refrigeration system NH3 indirect	X						
Heat recovery system - supplemental	X						
District heating - season	X					X	
District heating - off season	X	X	X	X	X	X	X
Distribution system	X		X		X	X	X

Table 6: System solution specifications.

6.2.1. Investment cost

As indicated in Table 6 above, all suggested replacements to the current system require investments in new refrigeration, heat recovery, and energy management systems respectively. Some solutions come with additional costs, e.g. due to a new distribution system (CO_2 direct), while other solutions can make use of existing components in the case ice rink. Furthermore, in this case context the price for a new machine room has also been added to the investment cost of each potential replacement system.

Investment and installation costs for each system solution have been investigated by reviewing past projects and receiving information from suppliers, consultants etc. Diversification of the sources for cost information has allowed for a detailed localization of individual costs. The costs have then been summed according to specifications, resulting in the total investment cost for each system that can be seen in Figure 36.

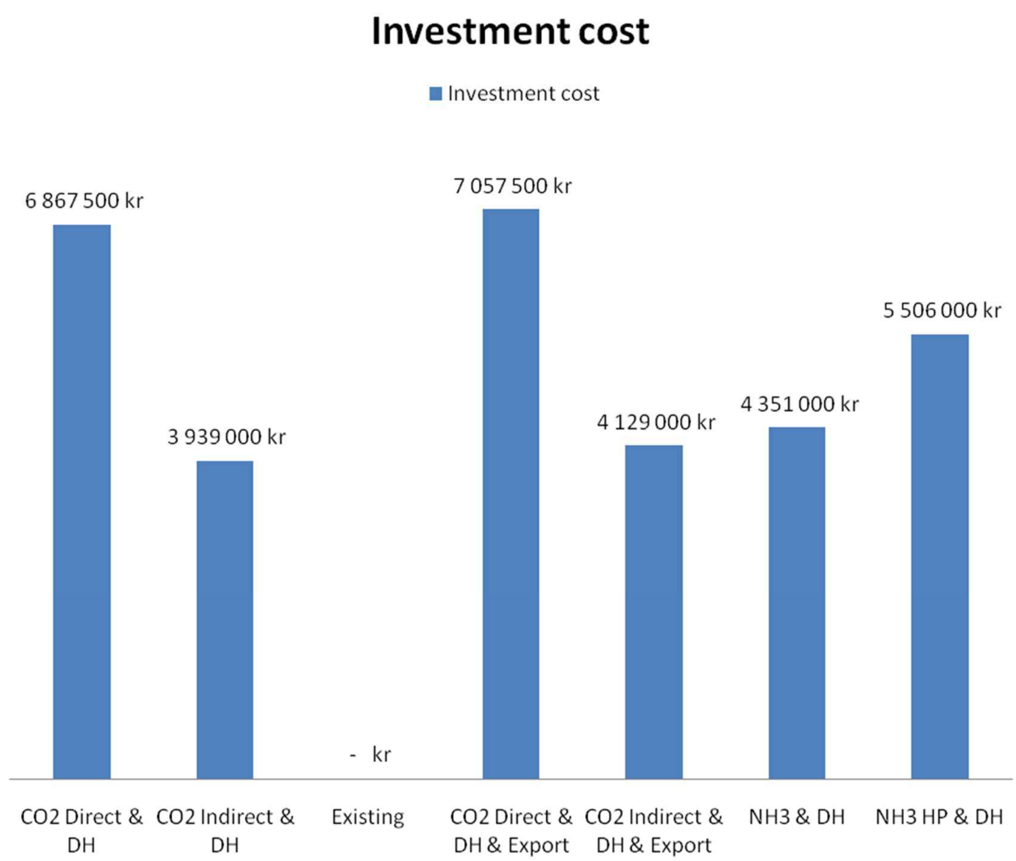

Figure 36: System solution investment cost.

As can be observed in Figure 36, CO_2 direct systems have a higher cost due to the required investment in a new distribution system. The indirect systems lie more or less in the same price range, apart from the variation of the NH_3 system that has a supplemental heat pump.

6.2.2. Operating cost

Simulations of monthly performance were performed for each system solution in order to compare their respective operating costs during a normal year in the case ice rink, while also taking into account local ambient conditions. The energy prices for electricity and district heating used in the calculations were based on existing data from local operators in the municipality. Both fixed and unit costs for energy were included in order to give a holistic picture of operating cost.

All system simulations have to fulfill the refrigeration and heating demands of the case ice rink. The facility lacks however detailed measurement of electricity consumption beyond the total consumption of the ice rink, which is necessary in order evaluate the monthly energy demands. Estimations of detailed electricity consumption were therefore calculated by reviewing the measured data, by reviewing the specifications of existing system components, and by applying results from previous studies in the field. The estimations can be seen in Table 7, where the actual measurements of total electricity consumption in the case ice rink are included in bold in the bottom row.

Electricity consumption in case ice rink (MWh)

	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	TOTAL	
Refrigeration system	22.5	45.0	45.0	45.0	45.0	45.0	40.0	35.0	322.5	56 %
Lighting	3.6	7.3	7.3	7.3	7.3	7.3	6.7	7.3	54.2	9 %
Dehumidification	9.7	19.8	19.8	9.5	9.5	9.5	6.7	7.3	91.8	16 %
Ventilation	3.6	7.3	7.3	7.3	7.3	7.3	6.7	7.3	54.2	9 %
Misc	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	56.0	10 %
TOTAL	46.4	86.4	86.4	76.2	76.2	76.2	67.2	64.0	578.8	100 %
Measured	**44.7**	**86.4**	**86.7**	**77.0**	**72.0**	**72.3**	**67.6**	**65.9**	**572**	Season
									43	Off season

Table 7: Current electricity consumption in case ice rink.

The results above apply for the existing system in the ice rink, while simulations of new system solutions require that the monthly energy demands be calculated. The refrigeration demand has been calculated by multiplying the electricity consumption of the existing refrigeration system with the monthly COP, as illustrated in Table 8. The COP values used here are based on measurements from other ice rinks with similar conditions.

Refrigeration in case ice rink (MWh)

	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	TOTAL
Refrigeration system	22.5	45.0	45.0	45.0	45.0	45.0	40.0	35.0	322.5
COP	2.1	2.3	2.5	2.6	2.6	2.6	2.6	2.4	
Refrigeration demand	47.3	103.5	112.8	115.5	117.7	117.9	104.0	82.7	**801**

Table 8: Refrigeration demand in case ice rink.

The heating demand of the ice rink has been calculated by summing the district heating consumption together with an estimation of recovered heat from the existing refrigeration system, as indicated in Table 9. Based on reviewed system structure and measurements from similar cases, it is estimated that 10% of the heat released is recovered from the existing refrigeration system. The heat released is the sum of the refrigeration demand and the added energy from compressor work.

Heating in case ice rink (MWh)

	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	TOTAL	Off season
District heating	6.5	15.9	34.2	46.7	63.2	65.5	67.1	60.9	359.9	60.1
Heat recovery	6.3	13.5	14.4	14.7	14.9	14.9	13.2	10.7	102.7	
Heating demand	12.8	29.4	48.6	61.4	78.1	80.4	80.3	71.6	462.7	

Table 9: Heating demand in case ice rink.

Simulations of how well new system solutions would perform in the case ice rink were done by dividing the refrigeration demand with each system's COP, and furthermore by calculating the amount of district heating required to accompany the heat recovered from each refrigeration system in order to fulfill the heating demand of the ice rink. The COP values in Table 10 take also into account the auxiliary components, i.e. pumps and fans, that are necessary in order to keep a system in operation.

COP of new systems

	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
CO_2 direct	2.5	2.7	2.8	2.9	2.9	2.9	2.9	2.8
CO_2 indirect	2.1	2.3	2.4	2.5	2.5	2.5	2.5	2.4
NH3 indirect	2.8	3.2	3.6	3.8	3.8	3.8	3.8	3.6

Table 10: COP of new system solutions.

It should be noted that the COP values for the CO_2 systems in Table 10 reflect heat recovery solutions that cover the total heating demand of the ice rink, whereas the values for the new NH_3 system don't. The NH_3 system must therefore continue the use of district heating during the season as well. This is however avoided in the system variation that includes a heat pump function. The pump is assumed to be a HFC pump with a constant COP of 4 during the whole season. District heating covers the off season heating demand of 60 MWh in all system solutions, see Table 9, since their respective refrigeration systems would all be shut down during that time.

Table 11 shows the estimations of excess heat that can be exported to nearby facilities during a year of operation. The heat released is the refrigeration demand added by the energy that comes from compressor work. Excess heat is calculated by removing the total heating demand of the case ice rink in Table 9 from the heat released. As mentioned before, excess heat must fulfill the temperature level demand of recipient buildings in order to be useful in their heating systems. Therefore, only the CO_2 systems are able to include options where heat is exported to the locker rooms of the nearby sports ground, whose total heating demand of 68 MWh during the season will be covered by the exported heat instead of the existing district heating system. The savings in energy consumption will be taken into account in the operating costs of the system solutions. Additional recipients won't be included at this stage, although there would be plenty of excess heat left over that still could be exported.

System	Heat released (MWh)	Excess heat (MWh)	Heat exported (MWh)
CO_2 direct	1086	623	68
CO_2 indirect	1128	666	68
NH_3 indirect	991	892	0

Table 11: Excess heat from system solutions and heat exported from case ice rink.

6.2.3. Service cost

Service related information for the different system solutions has been collected from existing ice rinks, reports, and experts in the field in order to produce service cost estimations that can be used in the analysis. Following the structure of the model used in the LCC analysis, the service costs have been divided into two groups: yearly costs and periodic costs. Yearly costs consist of scheduled yearly maintenance and error service cost estimations. Periodic costs are scheduled service costs that are higher in nature but occur less frequently, usually every 5-10 years. Periodic service costs reflect also the risk management of each system solution, as certain service procedures are scheduled in a preventive fashion well before vital parts, e.g. compressors, would break down.

Table 12 shows the mean values for service costs of each refrigeration system, where a yearly equivalent of periodic service costs has been calculated in order to give a general understanding of their size and impact on total service cost. The service costs of the system currently in use in the case ice rink have also been reviewed and added to the table. It can be observed that the current system has a higher yearly service cost than the mean value for NH_3 indirect systems. This is due to the increasing error service costs of the old system, which are expected to rise even further in the future as the years go by.

System solution	Yearly service	Periodic service	Total service
NH_3 - Existing system	120 000 kr	40 000 kr	160 000 kr
NH_3 - New indirect system	100 000 kr	40 000 kr	140 000 kr
CO_2 - Direct system	60 000 kr	25 000 kr	85 000 kr
CO_2 - Indirect system	55 000 kr	25 000 kr	80 000 kr

Table 12: System service costs.

6.2.4. Residual value

The economic lifespan of each system solution has been set to 20 years in the LCC analysis. This means that at the end of their lifecycles they have no residual value. However, there are a few large components in the system solutions that have shorter lifespans and need to be replaced while the systems are still in use (e.g. compressors in CO_2 systems). These actions are part of the scheduled periodic services described earlier, where the frequency of each service was gathered from suppliers and experts in the field. The remaining economic value of a component at the end of a system lifecycle has been taken into account as a residual value in the LCC calculations.

6.3. LCC analysis

An LCC analysis was conducted based on the previously described input data. Different methods for evaluating the financial performance of each system were used in order to give a broad understanding of which system solution would suit best for the case ice rink. Furthermore, the calculations have gone through a sensitivity and scenario analysis in order to test the robustness of the results and see how changes in economic outlook would affect the financial performance of each system. Full LCC material can be found in the Appendices of this study, while this section discusses the main findings of the analysis.

The results and figures presented in this chapter mainly reflect a normal economic outlook, where the nominal interest rate is set as 1,5% per year and the discount rate used by the municipality in their investment decision-making is 2,5%.

6.3.1. Present value method

The present value method collects all costs that occur during the life cycle of each system solution, and recalculates them to their respective present values. The resulting sum is called the total life-cycle cost, which can be interpreted as the lump sum that covers everything until the end of the economic lifespan.

As can be seen in Figure 37, the CO_2 indirect systems perform best in this analysis method due to their relatively low investment, operation, and service costs. The results can be well applied when comparing the new system solutions, since their economic lifespans of 20 years are valid assumptions. This is however not necessarily the case with the existing system, as there is a much higher risk that unforeseen major costs would occur due to its already old age.

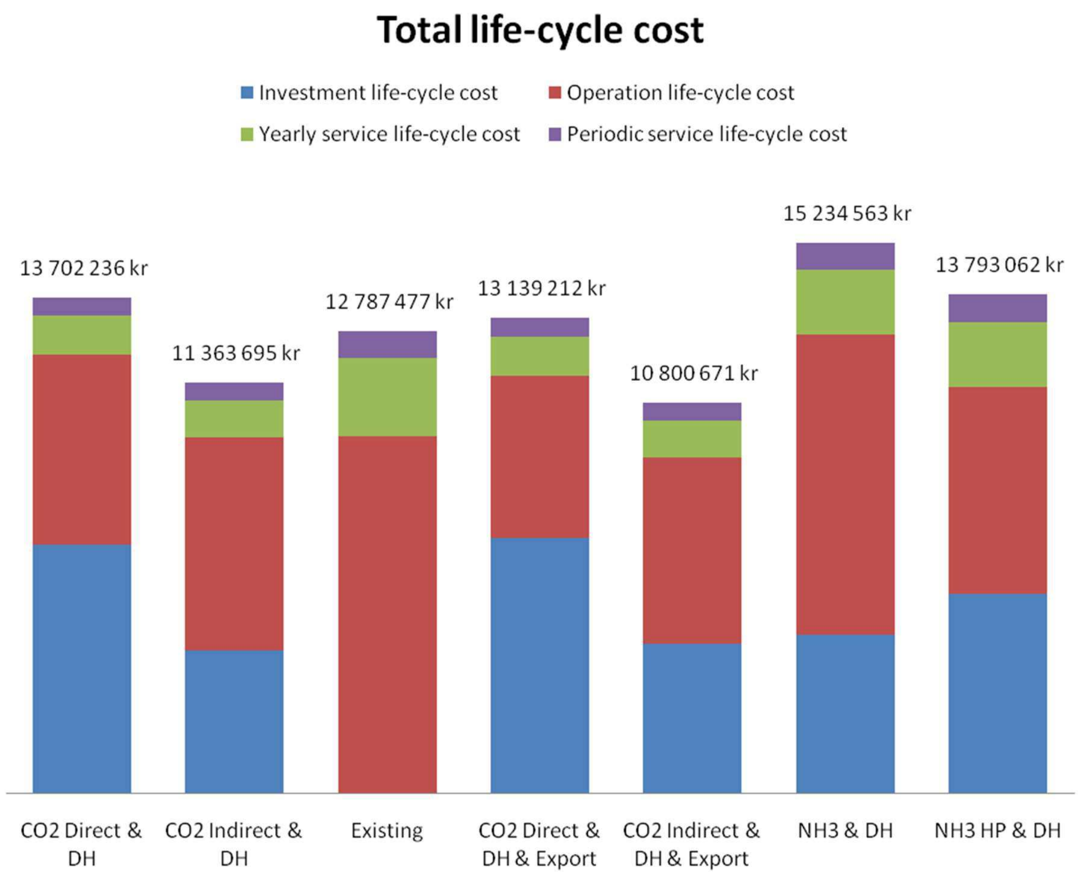

Figure 37: Total life-cycle cost of system solutions in case ice rink.

6.3.2. Equivalent annual cost method

The equivalent annual cost method takes the total life-cycle cost of each system and recalculates it into the annual cost of owning the system over its entire economic lifespan, i.e. the total annuity. Options with different economic lifespans can therefore be compared, making this method preferable over the present value method in this case context. It should be noted here that the total annuity of the existing system remains the same no matter what its economic lifespan would be, since it has no investment cost.

The results in Figure 38 indicate that switching to CO_2 indirect would be the best course of action for the case ice rink, even when considering the investment cost of the system in comparison to sticking with the current one. Furthermore, it can be observed that heat export to the locker rooms is profitable, making this variation of the CO_2 indirect system the most economic option.

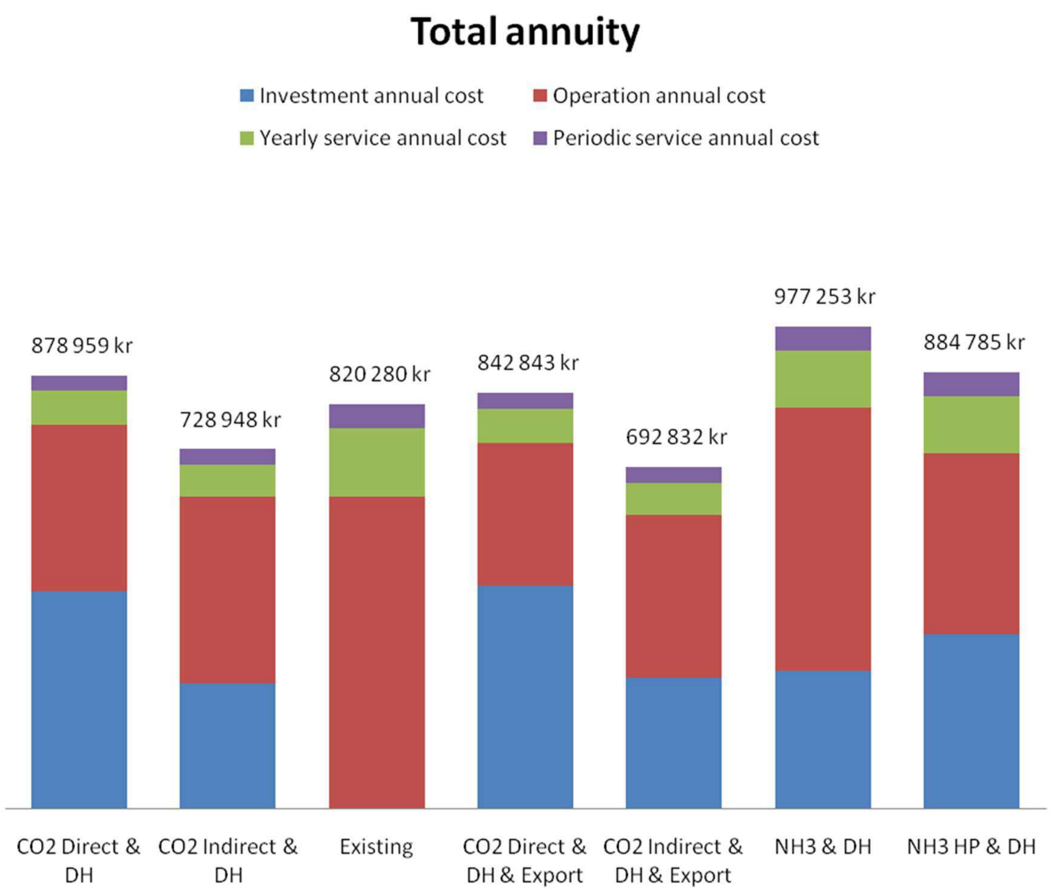

Figure 38: Total annuity of system solutions in case ice rink.

6.3.3. Payback method

The payback method calculates the cumulative costs of each system during a period of time. It therefore gives an understanding on how long it will take for an investment to pay itself back. Figure 39 shows that it takes about 11 years for a CO_2 indirect system to cumulatively cost less than the existing system in the case ice rink.

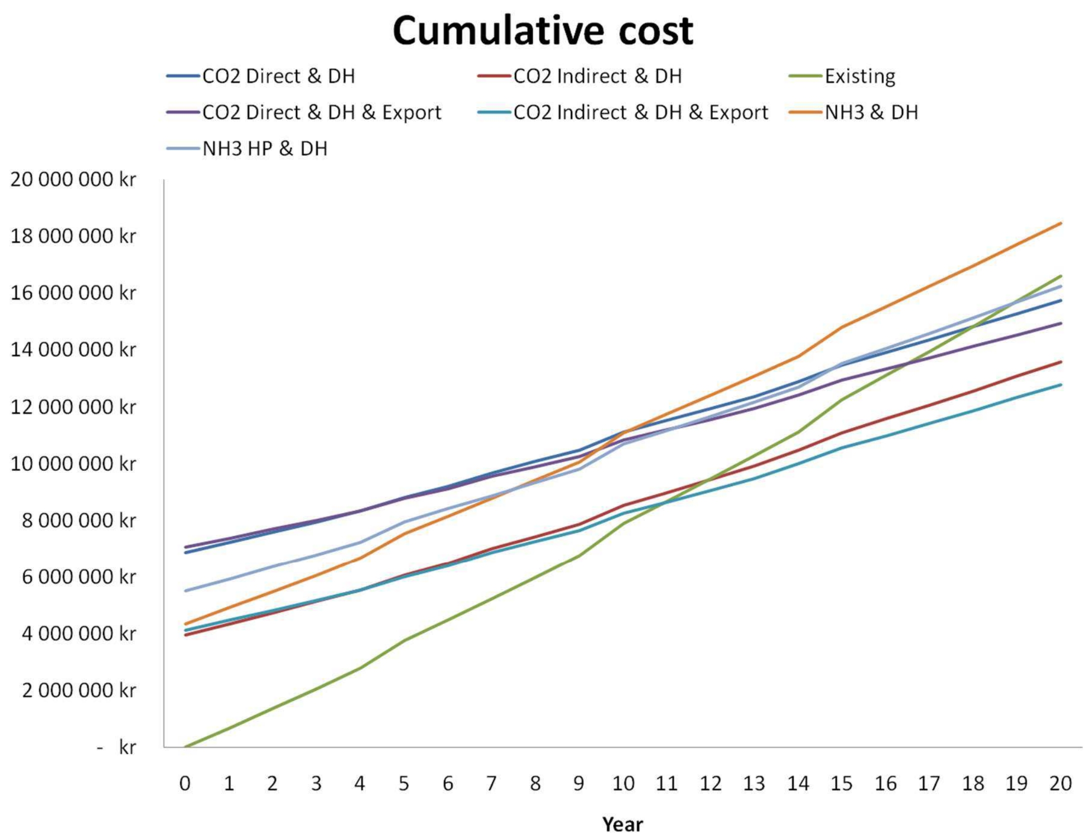

Figure 39: Cumulative costs of system solutions in case ice rink.

While the payback method usually is the easiest to understand, it does have its drawbacks. One drawback is that the time value of money is not taken into account, since future costs are not discounted. Another is that too much focus is placed on the payback time itself and not on the yearly savings that later turn into profit. Figure 40 shows the equivalent annual costs after investment, and illustrates how much money the municipality would save per year if it would implement another system solution to its ice rink. Here the yearly profit from the heat export function can also be observed, which in this case context is about 50 000 SEK.

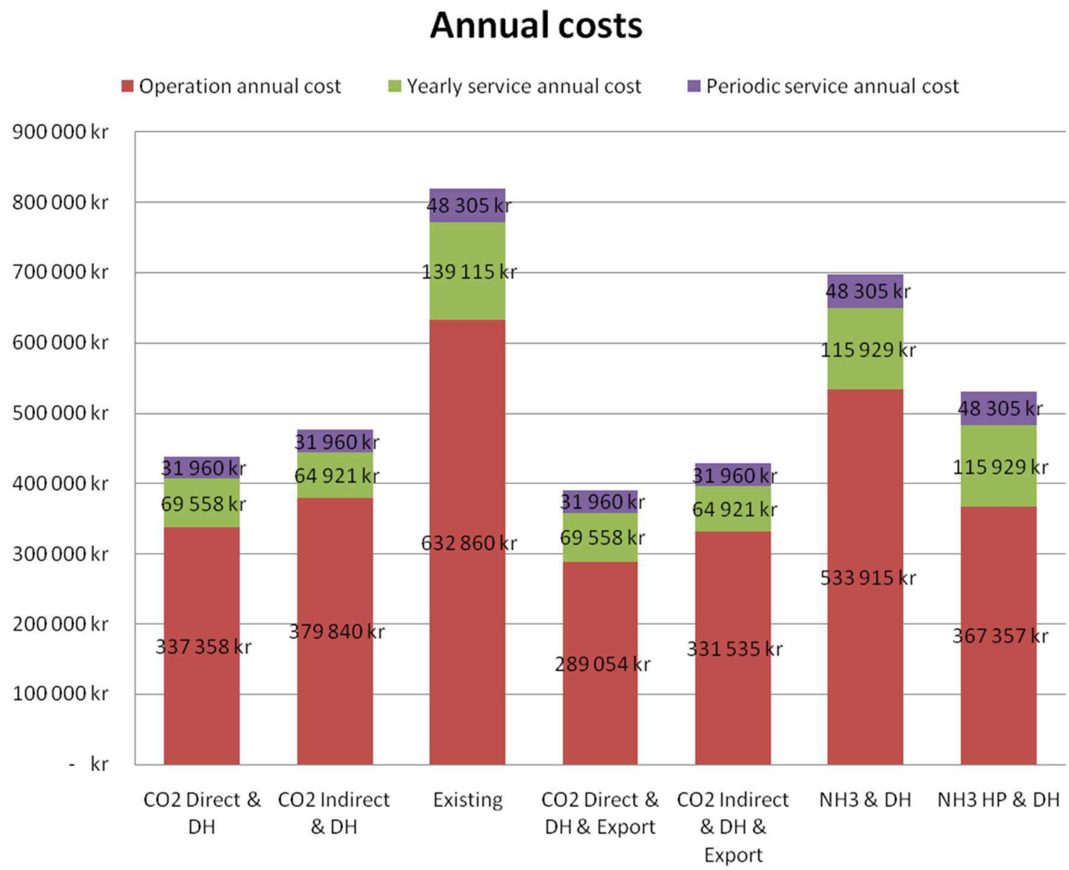

Figure 40: Equivalent annual costs after investment for systems solutions in case ice rink.

6.3.4. Discussion

Based on the results from the three methods described above, replacing the existing system with a CO_2 indirect system would be the most logical decision from a financial perspective. Furthermore, heat export proves to be a profitable option worth including. The locker rooms consume only a small part of the excess heat available from the refrigeration system, meaning that much greater savings can be achieved with the heat export function.

The sensitivity and scenario analysis show that the results are robust. It is quite likely that service costs of the existing system will rise remarkably in the coming years, see Appendices, which means that the financial advantages of implementing a new system might even be greater than what has been illustrated in this section. Further advantages could be achieved by installing a geothermal storage, which would eliminate the need for district heating during off season and improve heat export.

7. Conclusions

The objective of this study has been to develop an LCC analysis model that is effective and capable of producing reliable results. The model has also been tested in a case setting, where a municipality in Sweden requested to evaluate options for replacing the existing refrigeration system in its ice rink.

The developed model allows for effective handling of input data, making it possible to conduct a thorough LCC analysis of a refrigeration system. The sensitivity and scenario analysis tool plays a particularly important role when evaluating the quality of input data. The same tool also tests the robustness of the analyzed results, therefore determining their reliability which demonstrates the applicability of the developed model in comparative LCC analysis of refrigeration systems in ice rinks.

Input data was gathered from various sources, allowing for effective allocation of cost components. The quality of the data was further verified by the sensitivity and scenario tool of the LCC analysis model, which means that the results of the case investigation are conclusive. Circumstances change with time however, e.g. due to new developments in technology, which should make the input gathering a continuous process. This will keep the model updated and applicable in future case investigations where refrigeration system performance is evaluated.

Further development is required in the comparison of several system solutions. Since only three system solutions could be analyzed simultaneously in the model, the results had to be manually extracted to separate Excel sheets where a comparison between all systems could be done.

When the conclusions of the LCC analysis were presented to the municipality, an unexpected challenge turned out to be explaining the meaning of the results in an effective way so that decision-makers would correctly understand it. While the LCC analysis model illustrates the performance of system solutions from a profitability perspective, where the discount rate generally reflects the capital structure of the owner, the benefits of the analysis could perhaps be enhanced by presenting results that further have been translated to match the accounting policy of the client. Further research regarding the presentation LCC analysis results is nevertheless required.

Although the objective of this report has not been to give a general recommendation regarding the choice of refrigeration system for an ice rink, the LCC analysis in the case context does indicate that the CO_2-based technology is an option worthy of consideration. The financial benefits of the technology, mainly due to its low service cost and the excellent heat recovery properties of the refrigerant, can potentially be maximized with a well utilized heat export strategy. Similar results were obtained in a Canadian report, where an indirect CO_2 refrigeration system had the best financial performance in the LCC calculations (CanmetENERGY, 2013). This study concludes however that the financial performance of a refrigeration system in an ice rink only can be determined on a case context level.

An LCC analysis typically makes use of input data that is based on estimations. The data must therefore be handled properly in order to yield reliable results. While the developed model fulfills this objective, additional benefits can be achieved by minimizing the need for estimations. A critical factor here is the measurement of energy consumption on a detailed level, as many ice rinks only measure total consumption. New installations are therefore encouraged to incorporate this feature.

8. Suggestions for further research

The following observations and themes appeared while conducting this study and could be subject to further research:

- Expand the LCC analysis model to a Whole-life cost model, by including life-cycle assessment (LCA) that analyses environmental and social impact, including risks. This will broaden the scope of the developed model, and also make it applicable in contexts beyond this study.

- Investigate ways to enhance the presentation of LCC analysis results. One way could possibly be to research further into the accounting policies of facility owners, and integrate the findings into the model.

- Investigate the financial performances of refrigeration systems in various case settings in order to measure the maximum potential benefits of e.g. geothermal storages and the utilization of heat export.

- Continuously gather new input data for the model, and update the existing data whenever possible in order to maintain the model applicable for future case investigations of refrigeration system performance in ice rinks. The risk for outdated input data is real if the process isn't done continuously, as technologies advance quickly and policies change.

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Appendices

Appendix 1. LCC system comparison 1. 5 pages.
Appendix 2. LCC system comparison 2. 5 pages.
Appendix 3. LCC system comparison 3. 5 pages.
Appendix 4. LCC system comparison 4. 5 pages.
Appendix 5. LCC system comparison 5. 5 pages.
Appendix 6. LCC system comparison 6. 5 pages.

System comparison 1

Input data used in LCC
Important information

Scenario & sensitivity analysis

Cost of capital	2,5	%
Investment price level	100	%
Residual value price level	100	%
Periodic service price level	100	%
Yearly service price level	100	%
Electricity price level	100	%
District heating price level	100	%
Heat export to client price level	100	%

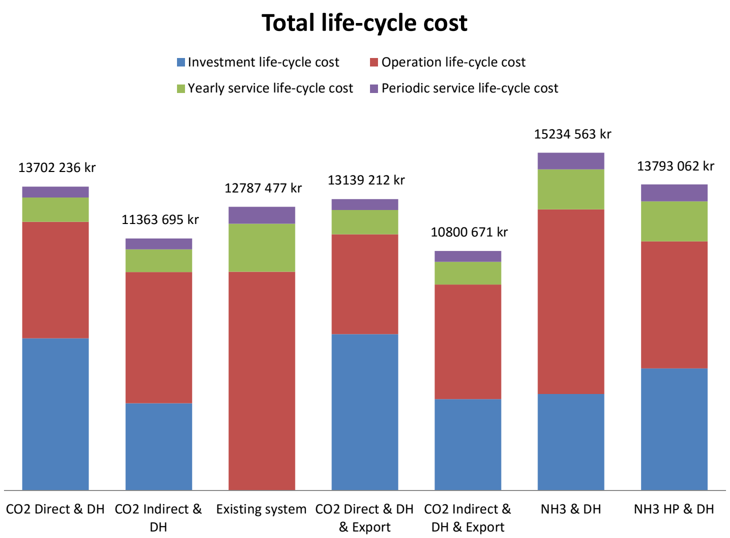
Displayed currency:	SEK
Currency multiplier:	1

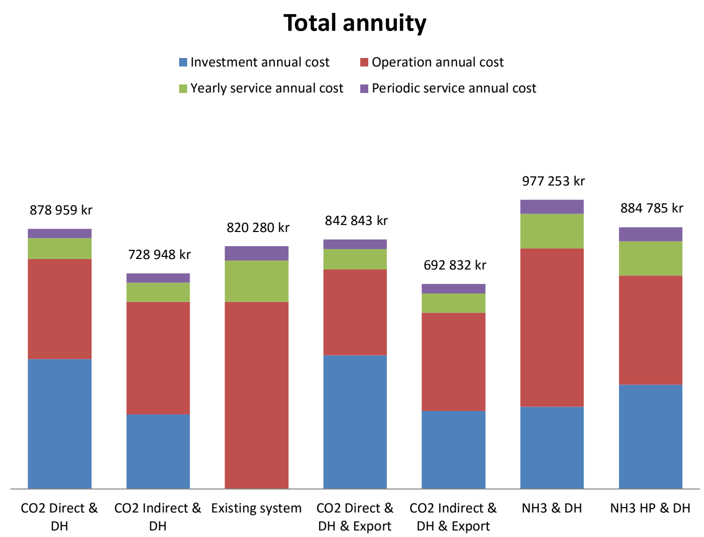
Residual value price escalation %:	0
Periodic service price escalation %:	1,5
Yearly service price escalation %:	1,5
Electricity price escalation %:	1,5
District heating price escalation %:	1,5
Heat export to client price esc. %:	1,5

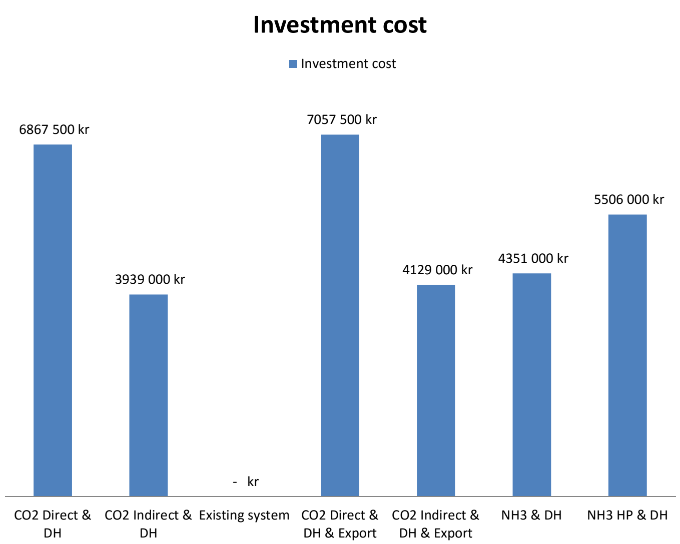
Comment:

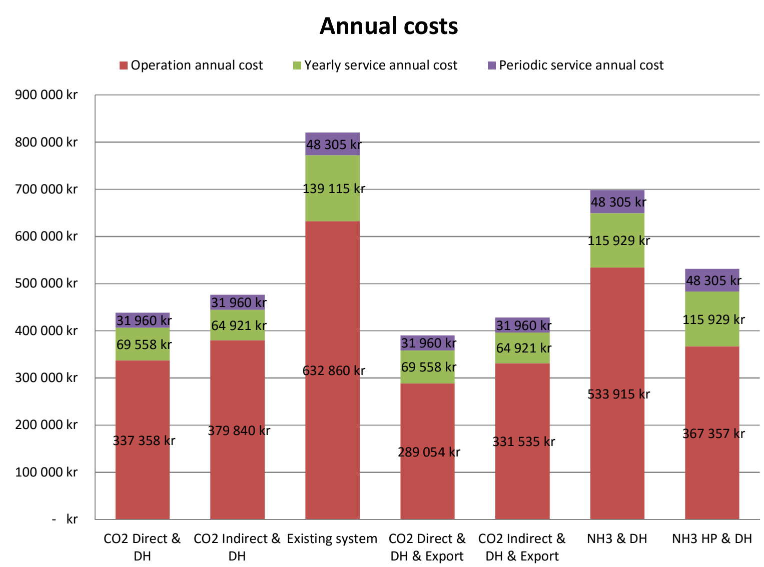
Analysis in a scenario with normal economic outlook. The discount rate of 2,5% is used by the municipality itself. The sum of inflation and escalation in price level is 1,5%.

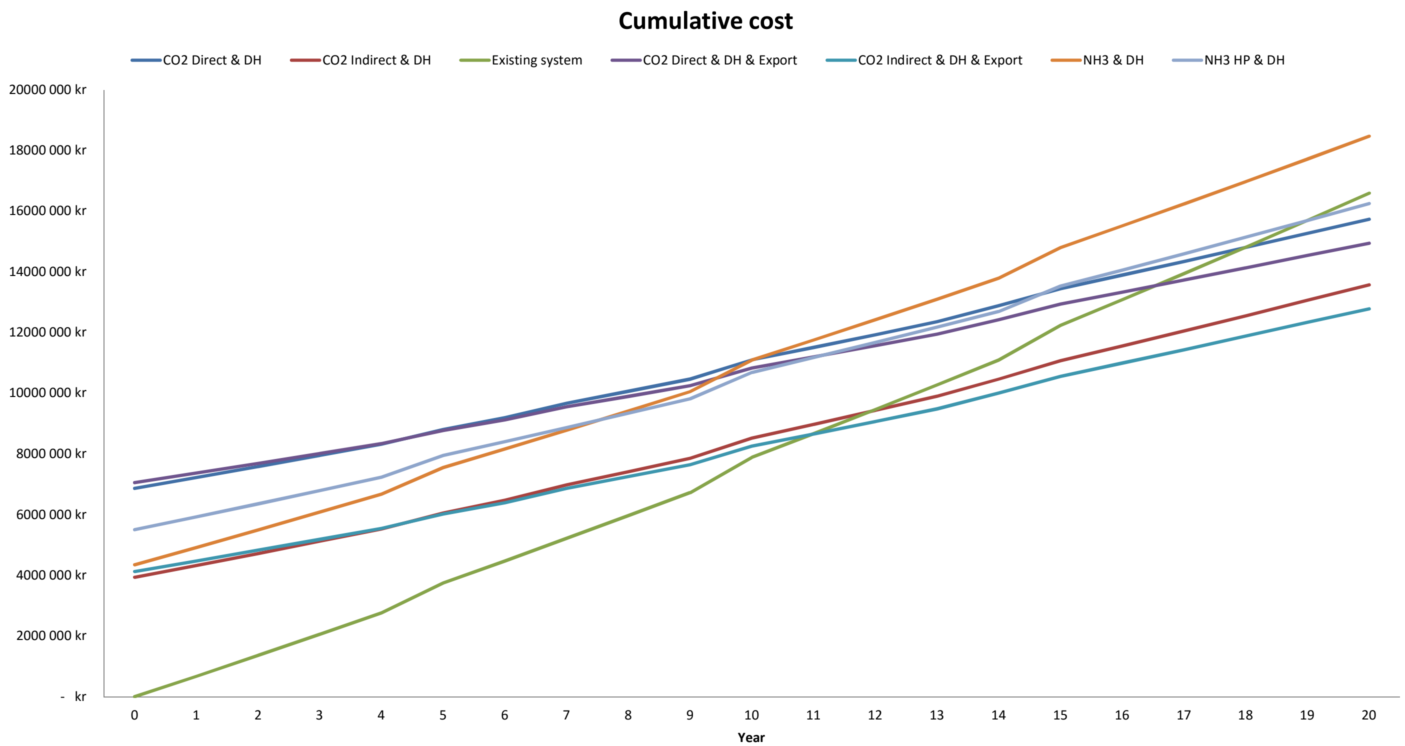
CO2-indirect systems generate the best results. Heat export is deemed a profitable investment.


Total life-cycle cost
Investment life-cycle cost
Operation life-cycle cost
Yearly service life-cycle cost
Periodic service life-cycle cost
13702 236 kr
11363 695 kr
12787 477 kr
13139 212 kr
10800 671 kr
15234 563 kr
13793 062 kr
CO2 Direct & DH
CO2 Indirect & DH
Existing system
CO2 Direct & DH & Export
CO2 Indirect & DH & Export
NH3 & DH
NH3 HP & DH


Total annuity
Investment annual cost
Operation annual cost
Yearly service annual cost
Periodic service annual cost
878 959 kr
728 948 kr
820 280 kr
842 843 kr
692 832 kr
977 253 kr
884 785 kr
CO2 Direct & DH
CO2 Indirect & DH
Existing system
CO2 Direct & DH & Export
CO2 Indirect & DH & Export
NH3 & DH
NH3 HP & DH


Investment cost
Investment cost
6867 500 kr
3939 000 kr
- kr
7057 500 kr
4129 000 kr
4351 000 kr
5506 000 kr
CO2 Direct & DH
CO2 Indirect & DH
Existing system
CO2 Direct & DH & Export
CO2 Indirect & DH & Export
NH3 & DH
NH3 HP & DH


Annual costs
Operation annual cost
Yearly service annual cost
Periodic service annual cost
900 000 kr
800 000 kr
700 000 kr
600 000 kr
500 000 kr
400 000 kr
300 000 kr
200 000 kr
100 000 kr
- kr
31 960 kr
69 558 kr
337 358 kr
31 960 kr
64 921 kr
379 840 kr
48 305 kr
139 115 kr
632 860 kr
31 960 kr
69 558 kr
289 054 kr
31 960 kr
64 921 kr
331 535 kr
48 305 kr
115 929 kr
533 915 kr
48 305 kr
115 929 kr
367 357 kr
CO2 Direct & DH
CO2 Indirect & DH
Existing system
CO2 Direct & DH & Export
CO2 Indirect & DH & Export
NH3 & DH
NH3 HP & DH


Cumulative cost
CO2 Direct & DH
CO2 Indirect & DH
Existing system
CO2 Direct & DH & Export
CO2 Indirect & DH & Export
NH3 & DH
NH3 HP & DH
20000 000 kr
18000 000 kr
16000 000 kr
14000 000 kr
12000 000 kr
10000 000 kr
8000 000 kr
6000 000 kr
4000 000 kr
2000 000 kr
- kr
0
1
2
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7
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9
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16
17
18
19
20
Year

System financial performance:

Starting point

	CO2 Direct & DH	CO2 Indirect & DH	Existing system	CO2 Direct & DH & Export	CO2 Indirect & DH & Export	NH3 & DH	NH3 HP & DH
Investment cost	6 867 500 kr	3 939 000 kr	- kr	7 057 500 kr	4 129 000 kr	4 351 000 kr	5 506 000 kr
Economic lifespan	20	20	20	20	20	20	20

Life-cycle costs

	CO2 Direct & DH	CO2 Indirect & DH	Existing system	CO2 Direct & DH & Export	CO2 Indirect & DH & Export	NH3 & DH	NH3 HP & DH
Investment life-cycle cost	6 860 525 kr	3 932 025 kr	- kr	7 050 525 kr	4 122 025 kr	4 351 000 kr	5 506 000 kr
Operation life-cycle cost	5 259 134 kr	5 921 383 kr	9 865 751 kr	4 506 110 kr	5 168 359 kr	8 323 287 kr	5 726 786 kr
Yearly service life-cycle cost	1 084 346 kr	1 012 056 kr	2 168 692 kr	1 084 346 kr	1 012 056 kr	1 807 243 kr	1 807 243 kr
Periodic service life-cycle cost	498 231 kr	498 231 kr	753 033 kr	498 231 kr	498 231 kr	753 033 kr	753 033 kr
Total Life-cycle cost	**13 702 236 kr**	**11 363 695 kr**	**12 787 477 kr**	**13 139 212 kr**	**10 800 671 kr**	**15 234 563 kr**	**13 793 062 kr**

Equivalent Annual Cost

	CO2 Direct & DH	CO2 Indirect & DH	Existing system	CO2 Direct & DH & Export	CO2 Indirect & DH & Export	NH3 & DH	NH3 HP & DH
Investment annual cost	440 083 kr	252 228 kr	- kr	452 271 kr	264 416 kr	279 104 kr	353 194 kr
Operation annual cost	337 358 kr	379 840 kr	632 860 kr	289 054 kr	331 535 kr	533 915 kr	367 357 kr
Yearly service annual cost	69 558 kr	64 921 kr	139 115 kr	69 558 kr	64 921 kr	115 929 kr	115 929 kr
Periodic service annual cost	31 960 kr	31 960 kr	48 305 kr	31 960 kr	31 960 kr	48 305 kr	48 305 kr
Total Annuity	**878 959 kr**	**728 948 kr**	**820 280 kr**	**842 843 kr**	**692 832 kr**	**977 253 kr**	**884 785 kr**

Cumulative cost

Year	CO2 Direct & DH	CO2 Indirect & DH	Existing system	CO2 Direct & DH & Export	CO2 Indirect & DH & Export	NH3 & DH	NH3 HP & DH
0	6 867 500 kr	3 939 000 kr	- kr	7 057 500 kr	4 129 000 kr	4 351 000 kr	5 506 000 kr
1	7 223 768 kr	4 328 402 kr	675 889 kr	7 371 476 kr	4 476 110 kr	4 919 960 kr	5 929 133 kr
2	7 585 380 kr	4 723 645 kr	1 361 916 kr	7 690 162 kr	4 828 427 kr	5 497 454 kr	6 358 613 kr
3	7 952 417 kr	5 124 817 kr	2 058 234 kr	8 013 628 kr	5 186 028 kr	6 083 611 kr	6 794 535 kr
4	8 324 959 kr	5 532 006 kr	2 764 997 kr	8 341 946 kr	5 548 993 kr	6 678 560 kr	7 236 995 kr
5	8 810 817 kr	6 053 031 kr	3 751 682 kr	8 782 917 kr	6 025 132 kr	7 551 754 kr	7 955 414 kr
6	9 194 619 kr	6 472 528 kr	4 479 806 kr	9 121 159 kr	6 399 068 kr	8 164 685 kr	8 411 248 kr
7	9 672 966 kr	6 987 104 kr	5 218 853 kr	9 553 261 kr	6 867 400 kr	8 786 810 kr	8 873 920 kr
8	10 068 368 kr	7 419 280 kr	5 968 985 kr	9 901 726 kr	7 252 639 kr	9 418 268 kr	9 343 532 kr
9	10 469 701 kr	7 857 939 kr	6 730 369 kr	10 255 418 kr	7 643 655 kr	10 059 197 kr	9 820 188 kr
10	11 097 557 kr	8 523 680 kr	7 886 152 kr	10 834 918 kr	8 261 040 kr	11 092 718 kr	10 686 972 kr
11	11 511 021 kr	8 975 597 kr	8 670 549 kr	11 199 300 kr	8 663 875 kr	11 753 019 kr	11 178 035 kr
12	11 930 687 kr	9 434 292 kr	9 466 712 kr	11 569 148 kr	9 072 753 kr	12 423 225 kr	11 676 464 kr
13	12 356 648 kr	9 899 868 kr	10 274 817 kr	11 944 544 kr	9 487 764 kr	13 103 483 kr	12 182 369 kr
14	12 887 538 kr	10 470 969 kr	11 095 044 kr	12 424 110 kr	10 007 541 kr	13 793 946 kr	12 695 863 kr
15	13 451 397 kr	11 075 640 kr	12 240 132 kr	12 935 876 kr	10 560 119 kr	14 807 323 kr	13 529 618 kr
16	13 896 814 kr	11 562 483 kr	13 085 150 kr	13 328 419 kr	10 994 087 kr	15 518 655 kr	14 058 632 kr
17	14 348 914 kr	12 056 628 kr	13 942 844 kr	13 726 850 kr	11 434 564 kr	16 240 657 kr	14 595 581 kr
18	14 807 794 kr	12 558 186 kr	14 813 403 kr	14 131 257 kr	11 881 649 kr	16 973 489 kr	15 140 585 kr
19	15 273 558 kr	13 067 267 kr	15 697 020 kr	14 541 731 kr	12 335 440 kr	17 717 313 kr	15 693 764 kr
20	15 734 880 kr	13 572 556 kr	16 593 892 kr	14 946 934 kr	12 784 609 kr	18 472 295 kr	16 255 240 kr

System technical performance:

	CO2 Direct & DH	CO2 Indirect & DH	Existing system	CO2 Direct & DH & Export	CO2 Indirect & DH & Export	NH3 & DH	NH3 HP & DH
COP							
Refrigeration	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Heating	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Combined	**3,8**	**3,4**	**1,8**	**3,8**	**3,4**	**2,1**	**3,5**
Energy consumption per year							
Refrigeration	0	0	0	0	0	0	0
Heating	0	0	0	0	0	0	0
Total	**344**	**387**	**743**	**344**	**387**	**644**	**374**

Selected system settings:

	CO2 Direct & DH	CO2 Indirect & DH	Existing system	CO2 Direct & DH & Export	CO2 Indirect & DH & Export	NH3 & DH	NH3 HP & DH
Distribution system							
Header material	Copper	Plastic	Plastic	Copper	Plastic	Plastic	Plastic
Rink piping material	Copper	Plastic	Plastic	Copper	Plastic	Plastic	Plastic
Thermal concrete layer	Disabled	Disabled	Disabled	Disabled	Disabled	Disabled	Disabled
Optional modules							
Heat recovery	Enabled	Enabled	Enabled	Enabled	Enabled	Enabled	Enabled
Geothermal heat storage	Disabled	Disabled	Disabled	Disabled	Disabled	Disabled	Disabled
Heat export	Disabled	Disabled	Disabled	Enabled	Enabled	Disabled	Disabled
External heat source	District heating	District heating	District Heating	District heating	District heating	District Heating	HP&DH

System comparison 2

Input data used in LCC
Important information

Scenario & sensitivity analysis

Cost of capital	2,5	%
Investment price level	100	%
Residual value price level	100	%
Periodic service price level	100	%
Yearly service price level	100	%
Electricity price level	100	%
District heating price level	100	%
Heat export to client price level	100	%

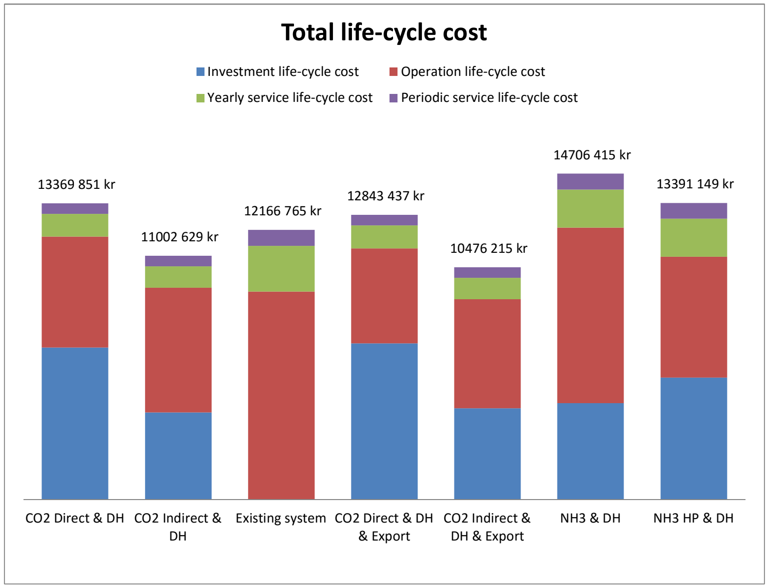
Displayed currency:	SEK
Currency multiplier:	1

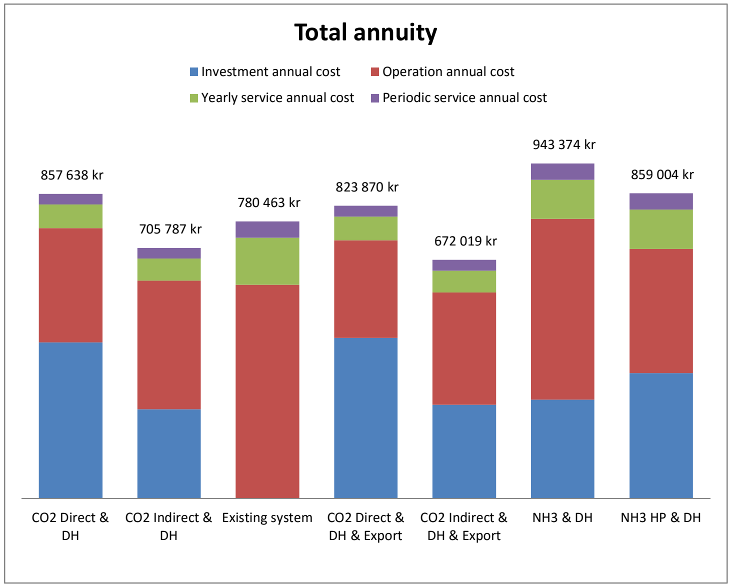
Residual value price escalation %:	0
Periodic service price escalation %:	1
Yearly service price escalation %:	1
Electricity price escalation %:	1
District heating price escalation %:	1
Heat export to client price esc. %:	1

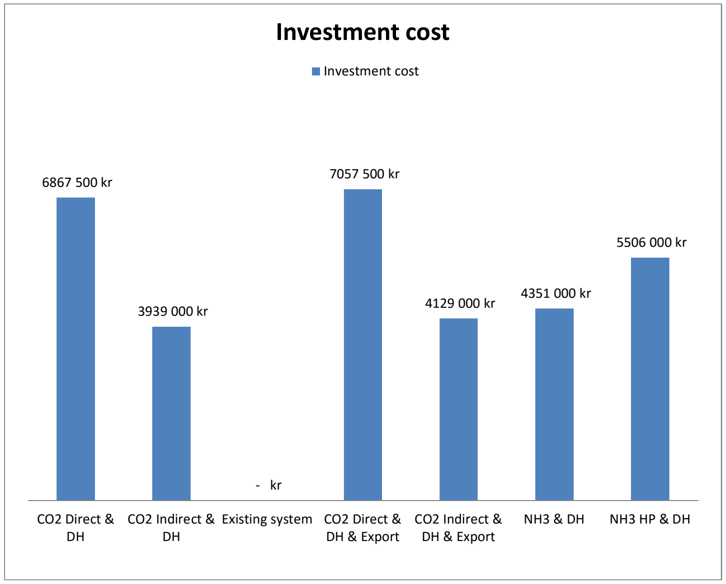
Comment:

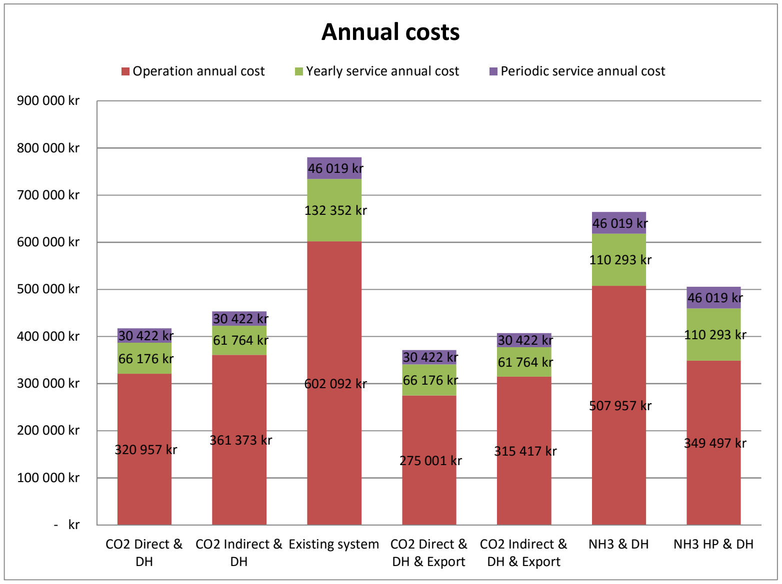
Scenario analysis with good economic outlook. The sum of inflation and escalation in price level has been decreased to 1%.

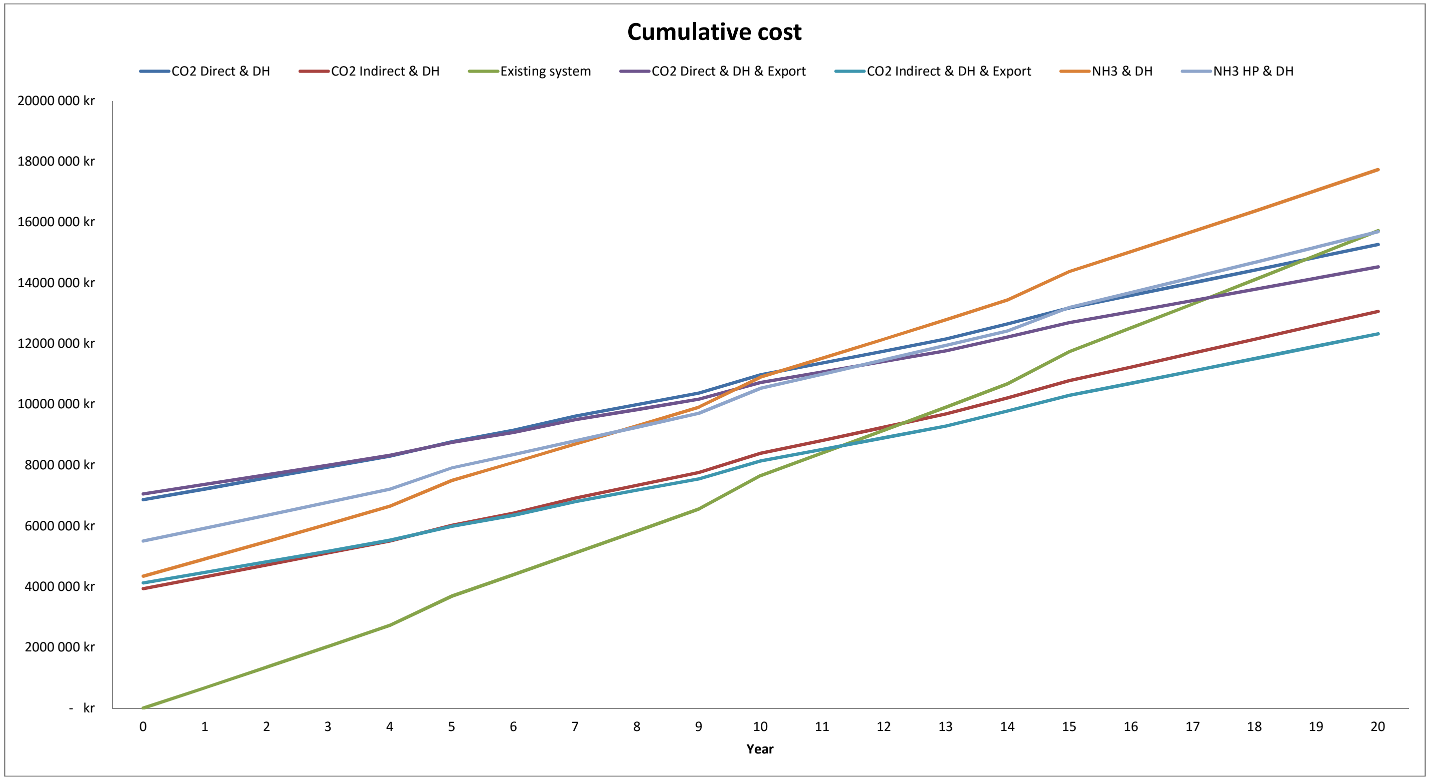
No significant change in end results.


Total life-cycle cost
Investment life-cycle cost
Operation life-cycle cost
Yearly service life-cycle cost
Periodic service life-cycle cost
13369 851 kr
11002 629 kr
12166 765 kr
12843 437 kr
10476 215 kr
14706 415 kr
13391 149 kr
CO2 Direct & DH
CO2 Indirect & DH
Existing system
CO2 Direct & DH & Export
CO2 Indirect & DH & Export
NH3 & DH
NH3 HP & DH


Total annuity
Investment annual cost
Operation annual cost
Yearly service annual cost
Periodic service annual cost
857 638 kr
705 787 kr
780 463 kr
823 870 kr
672 019 kr
943 374 kr
859 004 kr
CO2 Direct & DH
CO2 Indirect & DH
Existing system
CO2 Direct & DH & Export
CO2 Indirect & DH & Export
NH3 & DH
NH3 HP & DH


Investment cost
Investment cost
6867 500 kr
3939 000 kr
- kr
7057 500 kr
4129 000 kr
4351 000 kr
5506 000 kr
CO2 Direct & DH
CO2 Indirect & DH
Existing system
CO2 Direct & DH & Export
CO2 Indirect & DH & Export
NH3 & DH
NH3 HP & DH


Annual costs
Operation annual cost
Yearly service annual cost
Periodic service annual cost
900 000 kr
800 000 kr
700 000 kr
600 000 kr
500 000 kr
400 000 kr
300 000 kr
200 000 kr
100 000 kr
- kr
30 422 kr
66 176 kr
320 957 kr
30 422 kr
61 764 kr
361 373 kr
46 019 kr
132 352 kr
602 092 kr
30 422 kr
66 176 kr
275 001 kr
30 422 kr
61 764 kr
315 417 kr
46 019 kr
110 293 kr
507 957 kr
46 019 kr
110 293 kr
349 497 kr
CO2 Direct & DH
CO2 Indirect & DH
Existing system
CO2 Direct & DH & Export
CO2 Indirect & DH & Export
NH3 & DH
NH3 HP & DH


Cumulative cost
CO2 Direct & DH
CO2 Indirect & DH
Existing system
CO2 Direct & DH & Export
CO2 Indirect & DH & Export
NH3 & DH
NH3 HP & DH
20000 000 kr
18000 000 kr
16000 000 kr
14000 000 kr
12000 000 kr
10000 000 kr
8000 000 kr
6000 000 kr
4000 000 kr
2000 000 kr
- kr
0
1
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5
6
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8
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10
11
12
13
14
15
16
17
18
19
20
Year

System financial performance:

	CO2 Direct & DH	CO2 Indirect & DH	Existing system	CO2 Direct & DH & Export	CO2 Indirect & DH & Export	NH3 & DH	NH3 HP & DH
Starting point							
Investment cost	6 867 500 kr	3 939 000 kr	- kr	7 057 500 kr	4 129 000 kr	4 351 000 kr	5 506 000 kr
Economic lifespan	20	20	20	20	20	20	20
Life-cycle costs							
Investment life-cycle cost	6 860 525 kr	3 932 025 kr	- kr	7 050 525 kr	4 122 025 kr	4 351 000 kr	5 506 000 kr
Operation life-cycle cost	5 003 449 kr	5 633 502 kr	9 386 106 kr	4 287 035 kr	4 917 088 kr	7 918 631 kr	5 448 365 kr
Yearly service life-cycle cost	1 031 628 kr	962 853 kr	2 063 256 kr	1 031 628 kr	962 853 kr	1 719 380 kr	1 719 380 kr
Periodic service life-cycle cost	474 249 kr	474 249 kr	717 404 kr	474 249 kr	474 249 kr	717 404 kr	717 404 kr
Total Life-cycle cost	**13 369 851 kr**	**11 002 629 kr**	**12 166 765 kr**	**12 843 437 kr**	**10 476 215 kr**	**14 706 415 kr**	**13 391 149 kr**
Equivalent Annual Cost							
Investment annual cost	440 083 kr	252 228 kr	- kr	452 271 kr	264 416 kr	279 104 kr	353 194 kr
Operation annual cost	320 957 kr	361 373 kr	602 092 kr	275 001 kr	315 417 kr	507 957 kr	349 497 kr
Yearly service annual cost	66 176 kr	61 764 kr	132 352 kr	66 176 kr	61 764 kr	110 293 kr	110 293 kr
Periodic service annual cost	30 422 kr	30 422 kr	46 019 kr	30 422 kr	30 422 kr	46 019 kr	46 019 kr
Total Annuity	**857 638 kr**	**705 787 kr**	**780 463 kr**	**823 870 kr**	**672 019 kr**	**943 374 kr**	**859 004 kr**

Cumulative cost

Year	CO2 Direct & DH	CO2 Indirect & DH	Existing system	CO2 Direct & DH & Export	CO2 Indirect & DH & Export	NH3 & DH	NH3 HP & DH
0	6 867 500 kr	3 939 000 kr	- kr	7 057 500 kr	4 129 000 kr	4 351 000 kr	5 506 000 kr
1	7 222 013 kr	4 326 484 kr	672 560 kr	7 369 929 kr	4 474 400 kr	4 917 157 kr	5 927 048 kr
2	7 580 071 kr	4 717 842 kr	1 351 845 kr	7 685 483 kr	4 823 254 kr	5 488 976 kr	6 352 307 kr
3	7 941 710 kr	5 113 114 kr	2 037 923 kr	8 004 192 kr	5 175 597 kr	6 066 512 kr	6 781 819 kr
4	8 306 965 kr	5 512 339 kr	2 730 862 kr	8 326 089 kr	5 531 463 kr	6 649 825 kr	7 215 625 kr
5	8 780 974 kr	6 020 658 kr	3 693 482 kr	8 756 305 kr	5 995 989 kr	7 501 722 kr	7 916 523 kr
6	9 153 571 kr	6 427 907 kr	4 400 349 kr	9 084 672 kr	6 359 007 kr	8 096 759 kr	8 359 049 kr
7	9 615 665 kr	6 924 999 kr	5 114 285 kr	9 502 093 kr	6 811 427 kr	8 697 746 kr	8 806 000 kr
8	9 995 751 kr	7 340 434 kr	5 835 360 kr	9 837 059 kr	7 181 743 kr	9 304 743 kr	9 257 421 kr
9	10 379 638 kr	7 760 024 kr	6 563 645 kr	10 175 376 kr	7 555 762 kr	9 917 810 kr	9 713 356 kr
10	10 977 242 kr	8 393 687 kr	7 663 739 kr	10 726 953 kr	8 143 399 kr	10 901 533 kr	10 538 376 kr
11	11 368 845 kr	8 821 710 kr	8 406 663 kr	11 072 070 kr	8 524 936 kr	11 526 923 kr	11 003 475 kr
12	11 764 364 kr	9 254 014 kr	9 157 017 kr	11 420 638 kr	8 910 288 kr	12 158 566 kr	11 473 226 kr
13	12 163 838 kr	9 690 640 kr	9 914 874 kr	11 772 691 kr	9 299 493 kr	12 796 526 kr	11 947 674 kr
14	12 659 265 kr	10 223 591 kr	10 680 309 kr	12 220 223 kr	9 784 548 kr	13 440 866 kr	12 426 866 kr
15	13 182 866 kr	10 785 090 kr	11 743 641 kr	12 695 449 kr	10 297 674 kr	14 381 891 kr	13 201 093 kr
16	13 594 444 kr	11 234 947 kr	12 524 462 kr	13 058 170 kr	10 698 673 kr	15 039 182 kr	13 689 917 kr
17	14 010 139 kr	11 689 302 kr	13 313 091 kr	13 424 518 kr	11 103 681 kr	15 703 045 kr	14 183 629 kr
18	14 429 990 kr	12 148 201 kr	14 109 606 kr	13 794 530 kr	11 512 740 kr	16 373 548 kr	14 682 279 kr
19	14 854 040 kr	12 611 688 kr	14 914 087 kr	14 168 241 kr	11 925 890 kr	17 050 755 kr	15 185 915 kr
20	15 270 902 kr	13 068 382 kr	15 726 612 kr	14 534 262 kr	12 331 742 kr	17 734 735 kr	15 694 587 kr

System technical performance:

	CO2 Direct & DH	CO2 Indirect & DH	Existing system	CO2 Direct & DH & Export	CO2 Indirect & DH & Export	NH3 & DH	NH3 HP & DH
COP							
Refrigeration	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Heating	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Combined	**3,8**	**3,4**	**1,8**	**3,8**	**3,4**	**2,1**	**3,5**
Energy consumption per year							
Refrigeration	0	0	0	0	0	0	0
Heating	0	0	0	0	0	0	0
Total	**344**	**387**	**743**	**344**	**387**	**644**	**374**

Selected system settings:

	CO2 Direct & DH	CO2 Indirect & DH	Existing system	CO2 Direct & DH & Export	CO2 Indirect & DH & Export	NH3 & DH	NH3 HP & DH
Distribution system							
Header material	Copper	Plastic	Plastic	Copper	Plastic	Plastic	Plastic
Rink piping material	Copper	Plastic	Plastic	Copper	Plastic	Plastic	Plastic
Thermal concrete layer	Disabled	Disabled	Disabled	Disabled	Disabled	Disabled	Disabled
Optional modules							
Heat recovery	Enabled	Enabled	Enabled	Enabled	Enabled	Enabled	Enabled
Geothermal heat storage	Disabled	Disabled	Disabled	Disabled	Disabled	Disabled	Disabled
Heat export	Disabled	Disabled	Disabled	Enabled	Enabled	Disabled	Disabled
External heat source	District heating	District heating	District Heating	District heating	District heating	District Heating	HP&DH

System comparison 3

Input data used in LCC
Important information

Scenario & sensitivity analysis

Cost of capital	2,5	%
Investment price level	100	%
Residual value price level	100	%
Periodic service price level	100	%
Yearly service price level	100	%
Electricity price level	100	%
District heating price level	100	%
Heat export to client price level	100	%

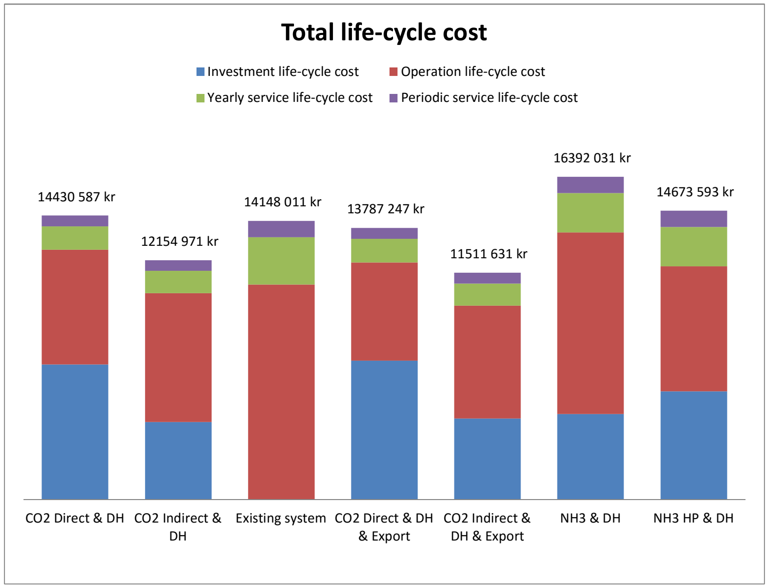
Displayed currency:	SEK
Currency multiplier:	1

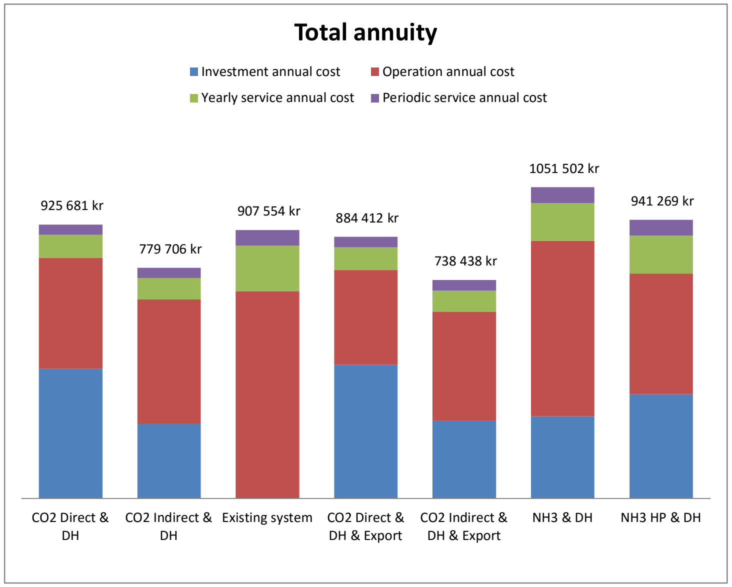
Residual value price escalation %:	0
Periodic service price escalation %:	2,5
Yearly service price escalation %:	2,5
Electricity price escalation %:	2,5
District heating price escalation %:	2,5
Heat export to client price esc. %:	2,5

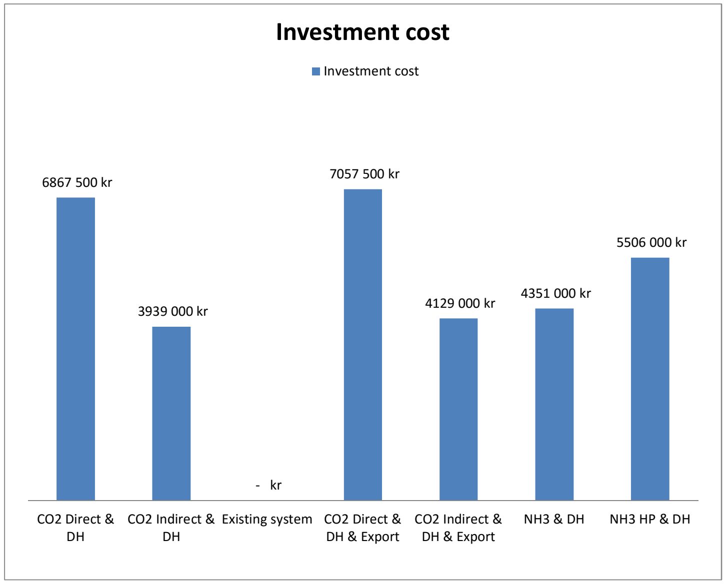
Comment:

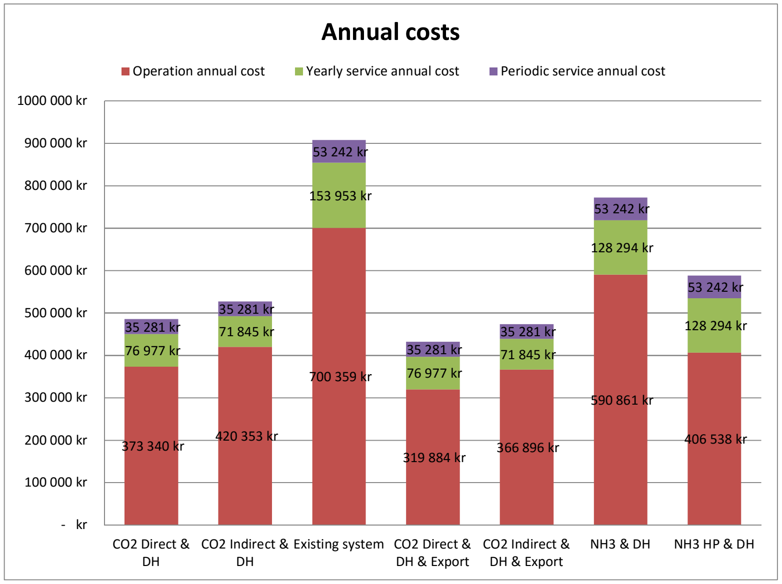
Scenario analysis in bad economic outlook. Sum of inflation and escalation in price level has been increased to 2,5%.

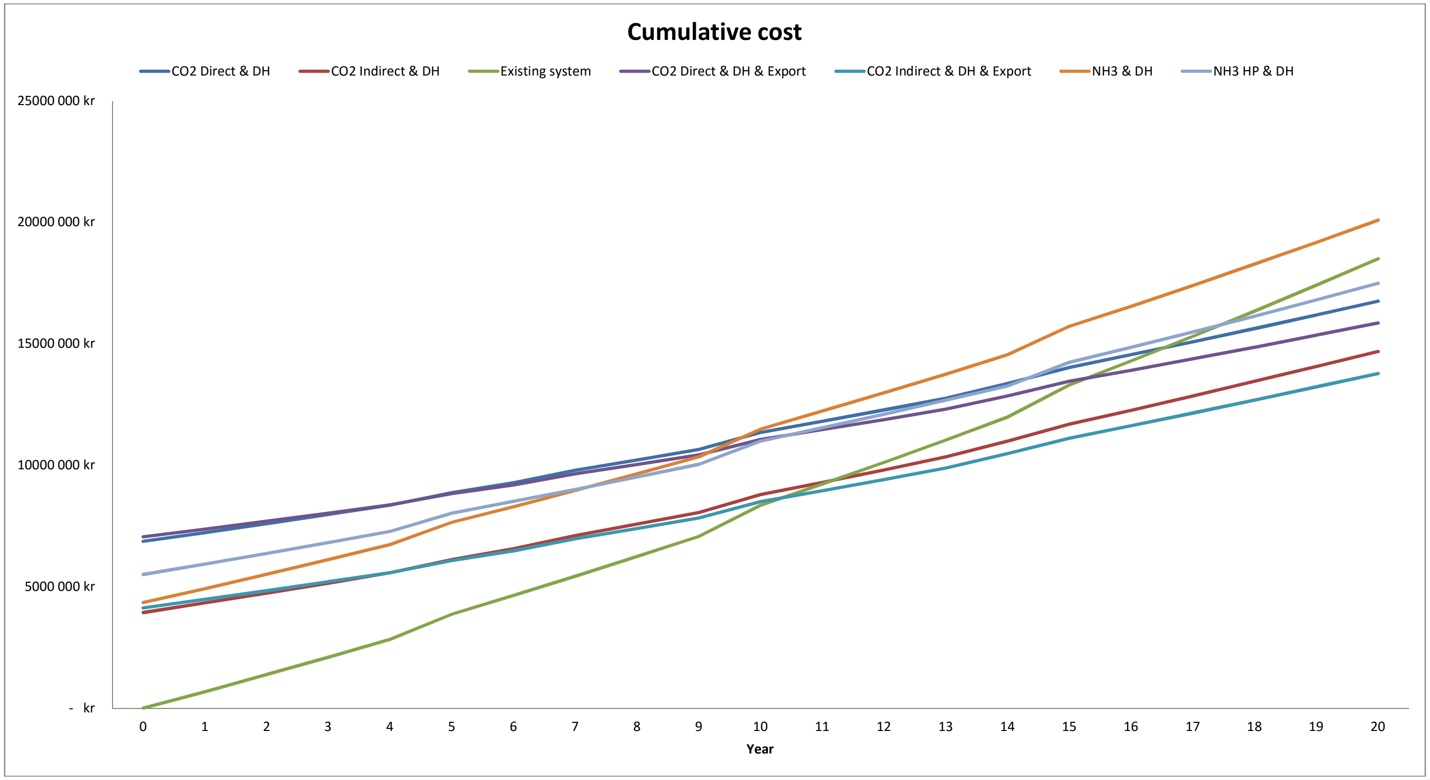
CO2-direct with heat export becoms a profitable option as well in this scenario.


Total life-cycle cost
Investment life-cycle cost
Operation life-cycle cost
Yearly service life-cycle cost
Periodic service life-cycle cost
14430 587 kr
12154 971 kr
14148 011 kr
13787 247 kr
11511 631 kr
16392 031 kr
14673 593 kr
CO2 Direct & DH
CO2 Indirect & DH
Existing system
CO2 Direct & DH & Export
CO2 Indirect & DH & Export
NH3 & DH
NH3 HP & DH


Total annuity
Investment annual cost
Operation annual cost
Yearly service annual cost
Periodic service annual cost
925 681 kr
779 706 kr
907 554 kr
884 412 kr
738 438 kr
1051 502 kr
941 269 kr
CO2 Direct & DH
CO2 Indirect & DH
Existing system
CO2 Direct & DH & Export
CO2 Indirect & DH & Export
NH3 & DH
NH3 HP & DH


Investment cost
Investment cost
6867 500 kr
3939 000 kr
- kr
7057 500 kr
4129 000 kr
4351 000 kr
5506 000 kr
CO2 Direct & DH
CO2 Indirect & DH
Existing system
CO2 Direct & DH & Export
CO2 Indirect & DH & Export
NH3 & DH
NH3 HP & DH


Annual costs
Operation annual cost
Yearly service annual cost
Periodic service annual cost
1000 000 kr
900 000 kr
800 000 kr
700 000 kr
600 000 kr
500 000 kr
400 000 kr
300 000 kr
200 000 kr
100 000 kr
- kr
35 281 kr
76 977 kr
373 340 kr
35 281 kr
71 845 kr
420 353 kr
53 242 kr
153 953 kr
700 359 kr
35 281 kr
76 977 kr
319 884 kr
35 281 kr
71 845 kr
366 896 kr
53 242 kr
128 294 kr
590 861 kr
53 242 kr
128 294 kr
406 538 kr
CO2 Direct & DH
CO2 Indirect & DH
Existing system
CO2 Direct & DH & Export
CO2 Indirect & DH & Export
NH3 & DH
NH3 HP & DH



Cumulative cost
CO2 Direct & DH
CO2 Indirect & DH
Existing system
CO2 Direct & DH & Export
CO2 Indirect & DH & Export
NH3 & DH
NH3 HP & DH
25000 000 kr
20000 000 kr
15000 000 kr
10000 000 kr
5000 000 kr
- kr
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
Year

System financial performance:

	CO2 Direct & DH	CO2 Indirect & DH	Existing system	CO2 Direct & DH & Export	CO2 Indirect & DH & Export	NH3 & DH	NH3 HP & DH
Starting point							
Investment cost	6 867 500 kr	3 939 000 kr	- kr	7 057 500 kr	4 129 000 kr	4 351 000 kr	5 506 000 kr
Economic lifespan	20	20	20	20	20	20	20
Life-cycle costs							
Investment life-cycle cost	6 860 525 kr	3 932 025 kr	- kr	7 050 525 kr	4 122 025 kr	4 351 000 kr	5 506 000 kr
Operation life-cycle cost	5 820 062 kr	6 552 945 kr	10 918 011 kr	4 986 722 kr	5 719 605 kr	9 211 031 kr	6 337 593 kr
Yearly service life-cycle cost	1 200 000 kr	1 120 000 kr	2 400 000 kr	1 200 000 kr	1 120 000 kr	2 000 000 kr	2 000 000 kr
Periodic service life-cycle cost	550 000 kr	550 000 kr	830 000 kr	550 000 kr	550 000 kr	830 000 kr	830 000 kr
Total Life-cycle cost	**14 430 587 kr**	**12 154 971 kr**	**14 148 011 kr**	**13 787 247 kr**	**11 511 631 kr**	**16 392 031 kr**	**14 673 593 kr**
Equivalent Annual Cost							
Investment annual cost	440 083 kr	252 228 kr	- kr	452 271 kr	264 416 kr	279 104 kr	353 194 kr
Operation annual cost	373 340 kr	420 353 kr	700 359 kr	319 884 kr	366 896 kr	590 861 kr	406 538 kr
Yearly service annual cost	76 977 kr	71 845 kr	153 953 kr	76 977 kr	71 845 kr	128 294 kr	128 294 kr
Periodic service annual cost	35 281 kr	35 281 kr	53 242 kr	35 281 kr	35 281 kr	53 242 kr	53 242 kr
Total Annuity	**925 681 kr**	**779 706 kr**	**907 554 kr**	**884 412 kr**	**738 438 kr**	**1 051 502 kr**	**941 269 kr**

Cumulative cost

Year	CO2 Direct & DH	CO2 Indirect & DH	Existing system	CO2 Direct & DH & Export	CO2 Indirect & DH & Export	NH3 & DH	NH3 HP & DH
0	6 867 500 kr	3 939 000 kr	- kr	7 057 500 kr	4 129 000 kr	4 351 000 kr	5 506 000 kr
1	7 227 278 kr	4 332 238 kr	682 548 kr	7 374 569 kr	4 479 530 kr	4 925 565 kr	5 933 302 kr
2	7 596 051 kr	4 735 308 kr	1 382 160 kr	7 699 566 kr	4 838 823 kr	5 514 495 kr	6 371 286 kr
3	7 974 043 kr	5 148 454 kr	2 099 262 kr	8 032 687 kr	5 207 098 kr	6 118 147 kr	6 820 220 kr
4	8 361 484 kr	5 571 929 kr	2 834 292 kr	8 374 136 kr	5 584 580 kr	6 736 892 kr	7 280 377 kr
5	8 871 753 kr	6 119 131 kr	3 870 549 kr	8 837 262 kr	6 084 640 kr	7 653 956 kr	8 034 890 kr
6	9 278 809 kr	6 564 045 kr	4 642 790 kr	9 195 997 kr	6 481 233 kr	8 304 024 kr	8 518 342 kr
7	9 791 136 kr	7 115 175 kr	5 434 336 kr	9 658 796 kr	6 982 835 kr	8 970 344 kr	9 013 881 kr
8	10 218 799 kr	7 582 612 kr	6 245 671 kr	10 035 692 kr	7 399 504 kr	9 653 321 kr	9 521 809 kr
9	10 657 154 kr	8 061 735 kr	7 077 290 kr	10 422 010 kr	7 826 591 kr	10 353 373 kr	10 042 434 kr
10	11 349 684 kr	8 796 052 kr	8 352 127 kr	11 061 202 kr	8 507 571 kr	11 493 355 kr	10 998 503 kr
11	11 810 230 kr	9 299 431 kr	9 225 846 kr	11 467 078 kr	8 956 278 kr	12 228 847 kr	11 545 485 kr
12	12 282 291 kr	9 815 394 kr	10 121 408 kr	11 883 101 kr	9 416 204 kr	12 982 726 kr	12 106 142 kr
13	12 766 152 kr	10 344 256 kr	11 039 359 kr	12 309 524 kr	9 887 627 kr	13 755 453 kr	12 680 815 kr
14	13 375 148 kr	10 999 377 kr	11 980 260 kr	12 859 646 kr	10 483 875 kr	14 547 498 kr	13 269 855 kr
15	14 028 335 kr	11 699 843 kr	13 306 757 kr	13 452 486 kr	11 123 994 kr	15 721 418 kr	14 235 696 kr
16	14 549 401 kr	12 269 369 kr	14 295 290 kr	13 911 698 kr	11 631 665 kr	16 553 560 kr	14 854 556 kr
17	15 083 494 kr	12 853 134 kr	15 308 536 kr	14 382 389 kr	12 152 029 kr	17 406 505 kr	15 488 888 kr
18	15 630 939 kr	13 451 493 kr	16 347 114 kr	14 864 848 kr	12 685 401 kr	18 280 774 kr	16 139 078 kr
19	16 192 070 kr	14 064 810 kr	17 411 656 kr	15 359 368 kr	13 232 108 kr	19 176 900 kr	16 805 522 kr
20	16 755 801 kr	14 682 032 kr	18 502 812 kr	15 854 823 kr	13 781 054 kr	20 095 429 kr	17 488 628 kr

System technical performance:

	CO2 Direct & DH	CO2 Indirect & DH	Existing system	CO2 Direct & DH & Export	CO2 Indirect & DH & Export	NH3 & DH	NH3 HP & DH
COP							
Refrigeration	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Heating	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Combined	**3,8**	**3,4**	**1,8**	**3,8**	**3,4**	**2,1**	**3,5**
Energy consumption per year							
Refrigeration	0	0	0	0	0	0	0
Heating	0	0	0	0	0	0	0
Total	**344**	**387**	**743**	**344**	**387**	**644**	**374**

Selected system settings:

	CO2 Direct & DH	CO2 Indirect & DH	Existing system	CO2 Direct & DH & Export	CO2 Indirect & DH & Export	NH3 & DH	NH3 HP & DH
Distribution system							
Header material	Copper	Plastic	Plastic	Copper	Plastic	Plastic	Plastic
Rink piping material	Copper	Plastic	Plastic	Copper	Plastic	Plastic	Plastic
Thermal concrete layer	Disabled	Disabled	Disabled	Disabled	Disabled	Disabled	Disabled
Optional modules							
Heat recovery	Enabled	Enabled	Enabled	Enabled	Enabled	Enabled	Enabled
Geothermal heat storage	Disabled	Disabled	Disabled	Disabled	Disabled	Disabled	Disabled
Heat export	Disabled	Disabled	Disabled	Enabled	Enabled	Disabled	Disabled
External heat source	District heating	District heating	District Heating	District heating	District heating	District Heating	HP&DH

System comparison 4

Input data used in LCC
Important information

Scenario & sensitivity analysis

Cost of capital	1,5	%
Investment price level	100	%
Residual value price level	100	%
Periodic service price level	100	%
Yearly service price level	100	%
Electricity price level	100	%
District heating price level	100	%
Heat export to client price level	100	%

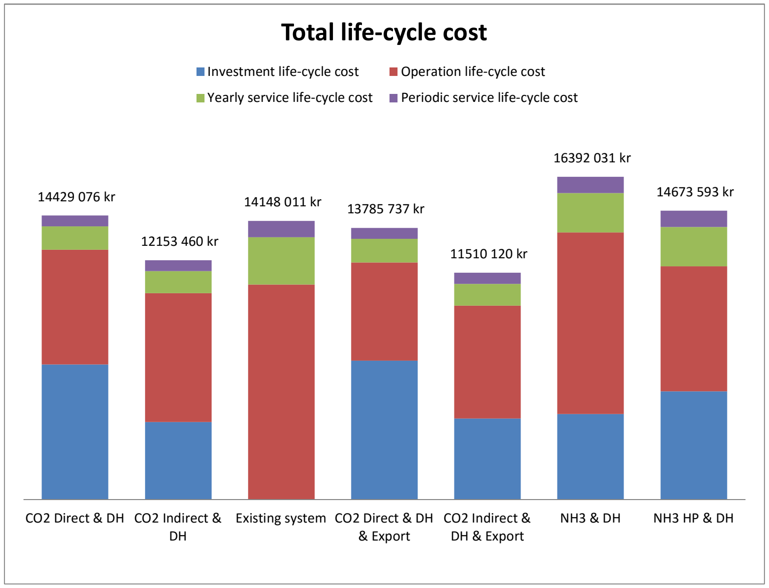
Displayed currency:	SEK
Currency multiplier:	1

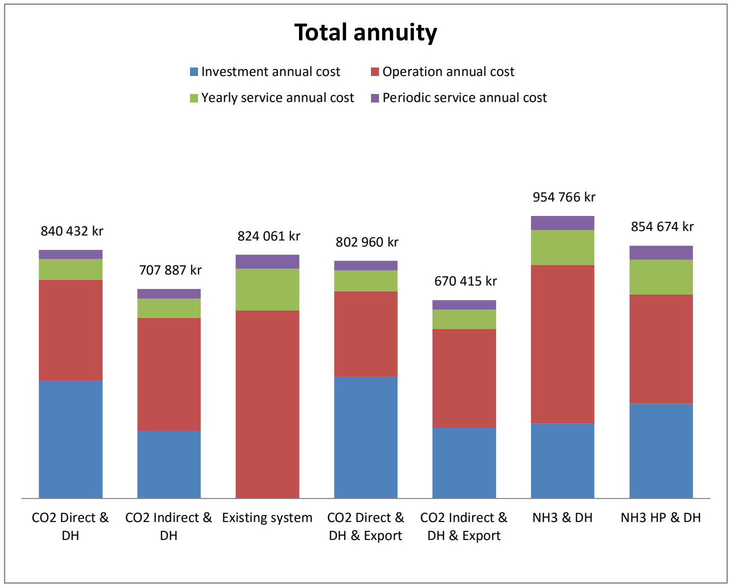
Residual value price escalation %:	0
Periodic service price escalation %:	1,5
Yearly service price escalation %:	1,5
Electricity price escalation %:	1,5
District heating price escalation %:	1,5
Heat export to client price esc. %:	1,5

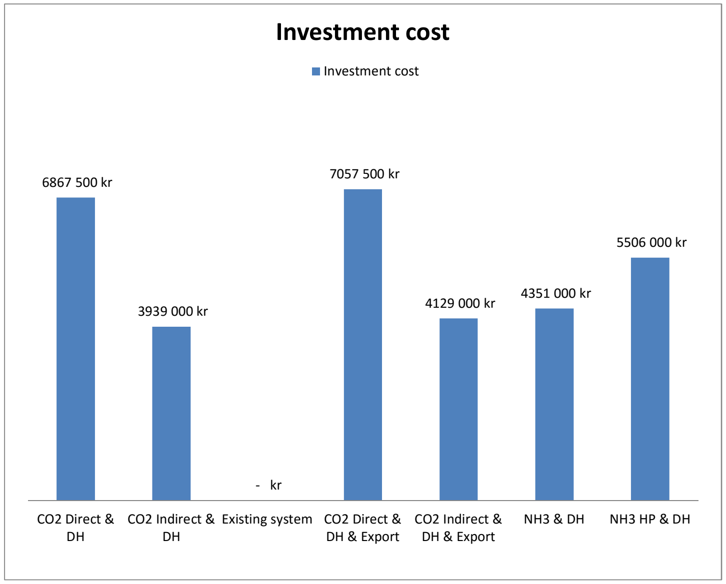
Comment:

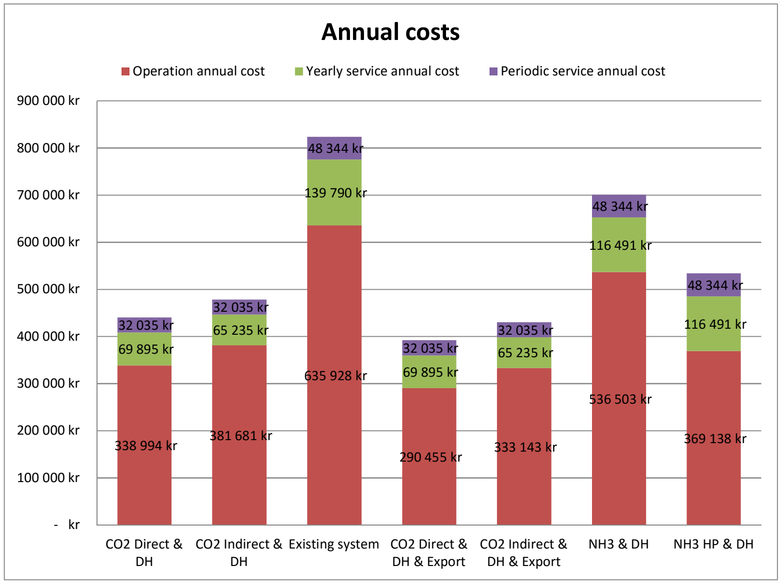
Normal economic outlook. The discount rate is lowered to 1,5%.

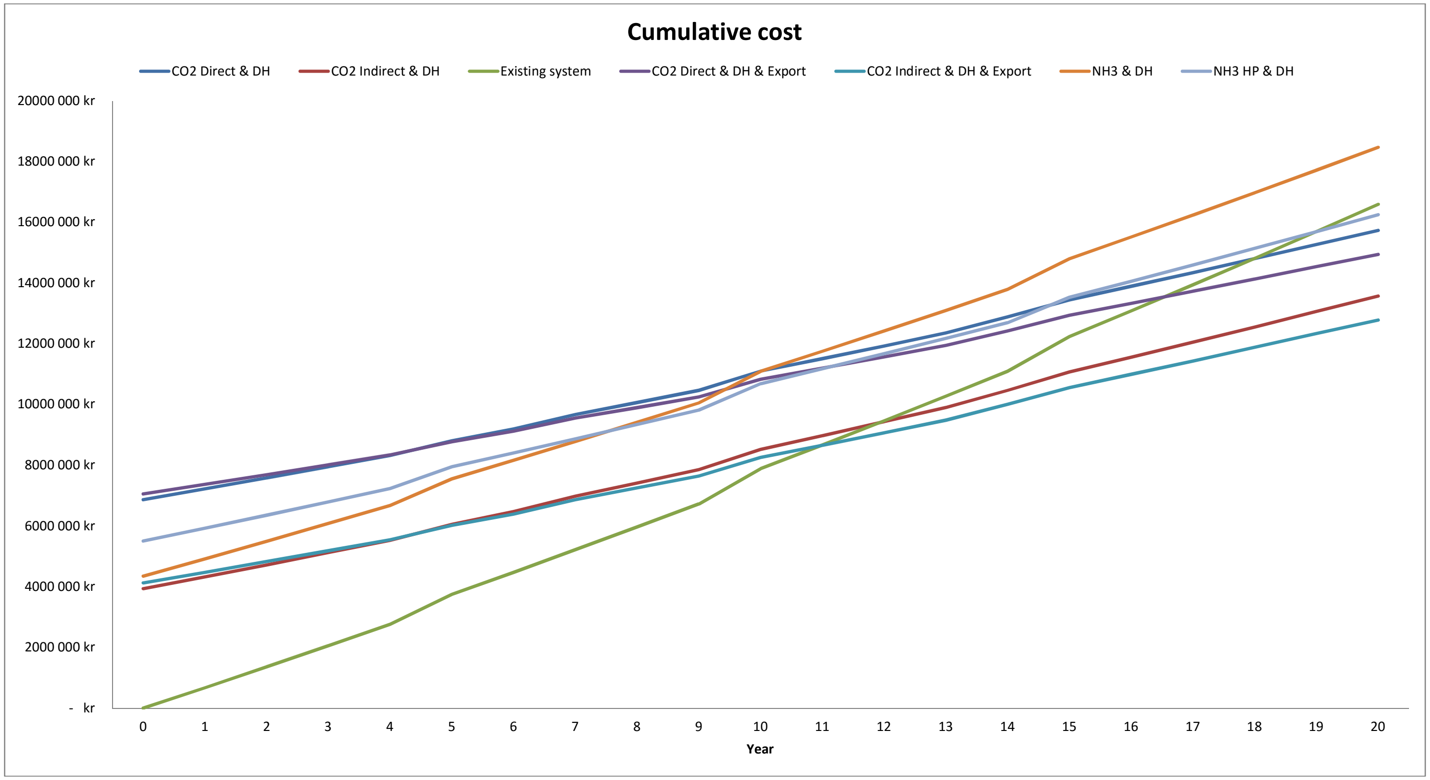
Future costs become more important when the discount rate is lower.
Therefore CO2-based systems with their low operating cost are in favor here.


Total life-cycle cost
Investment life-cycle cost
Operation life-cycle cost
Yearly service life-cycle cost
Periodic service life-cycle cost
14429 076 kr
12153 460 kr
14148 011 kr
13785 737 kr
11510 120 kr
16392 031 kr
14673 593 kr
CO2 Direct & DH
CO2 Indirect & DH
Existing system
CO2 Direct & DH & Export
CO2 Indirect & DH & Export
NH3 & DH
NH3 HP & DH


Total annuity
Investment annual cost
Operation annual cost
Yearly service annual cost
Periodic service annual cost
840 432 kr
707 887 kr
824 061 kr
802 960 kr
670 415 kr
954 766 kr
854 674 kr
CO2 Direct & DH
CO2 Indirect & DH
Existing system
CO2 Direct & DH & Export
CO2 Indirect & DH & Export
NH3 & DH
NH3 HP & DH


Investment cost
Investment cost
6867 500 kr
3939 000 kr
- kr
7057 500 kr
4129 000 kr
4351 000 kr
5506 000 kr
CO2 Direct & DH
CO2 Indirect & DH
Existing system
CO2 Direct & DH & Export
CO2 Indirect & DH & Export
NH3 & DH
NH3 HP & DH


Annual costs
Operation annual cost
Yearly service annual cost
Periodic service annual cost
900 000 kr
800 000 kr
700 000 kr
600 000 kr
500 000 kr
400 000 kr
300 000 kr
200 000 kr
100 000 kr
- kr
32 035 kr
69 895 kr
338 994 kr
32 035 kr
65 235 kr
381 681 kr
48 344 kr
139 790 kr
635 928 kr
32 035 kr
69 895 kr
290 455 kr
32 035 kr
65 235 kr
333 143 kr
48 344 kr
116 491 kr
536 503 kr
48 344 kr
116 491 kr
369 138 kr
CO2 Direct & DH
CO2 Indirect & DH
Existing system
CO2 Direct & DH & Export
CO2 Indirect & DH & Export
NH3 & DH
NH3 HP & DH


Cumulative cost
CO2 Direct & DH
CO2 Indirect & DH
Existing system
CO2 Direct & DH & Export
CO2 Indirect & DH & Export
NH3 & DH
NH3 HP & DH
20000 000 kr
18000 000 kr
16000 000 kr
14000 000 kr
12000 000 kr
10000 000 kr
8000 000 kr
6000 000 kr
4000 000 kr
2000 000 kr
- kr
0
1
2
3
4
5
6
7
8
9
10
11
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14
15
16
17
18
19
20
Year

System financial performance:

	CO2 Direct & DH	CO2 Indirect & DH	Existing system	CO2 Direct & DH & Export	CO2 Indirect & DH & Export	NH3 & DH	NH3 HP & DH
Starting point							
Investment cost	6 867 500 kr	3 939 000 kr	- kr	7 057 500 kr	4 129 000 kr	4 351 000 kr	5 506 000 kr
Economic lifespan	20	20	20	20	20	20	20
Life-cycle costs							
Investment life-cycle cost	6 859 015 kr	3 930 515 kr	- kr	7 049 015 kr	4 120 515 kr	4 351 000 kr	5 506 000 kr
Operation life-cycle cost	5 820 062 kr	6 552 945 kr	10 918 011 kr	4 986 722 kr	5 719 605 kr	9 211 031 kr	6 337 593 kr
Yearly service life-cycle cost	1 200 000 kr	1 120 000 kr	2 400 000 kr	1 200 000 kr	1 120 000 kr	2 000 000 kr	2 000 000 kr
Periodic service life-cycle cost	550 000 kr	550 000 kr	830 000 kr	550 000 kr	550 000 kr	830 000 kr	830 000 kr
Total Life-cycle cost	**14 429 076 kr**	**12 153 460 kr**	**14 148 011 kr**	**13 785 737 kr**	**11 510 120 kr**	**16 392 031 kr**	**14 673 593 kr**
Equivalent Annual Cost							
Investment annual cost	399 508 kr	228 936 kr	- kr	410 575 kr	240 002 kr	253 427 kr	320 701 kr
Operation annual cost	338 994 kr	381 681 kr	635 928 kr	290 455 kr	333 143 kr	536 503 kr	369 138 kr
Yearly service annual cost	69 895 kr	65 235 kr	139 790 kr	69 895 kr	65 235 kr	116 491 kr	116 491 kr
Periodic service annual cost	32 035 kr	32 035 kr	48 344 kr	32 035 kr	32 035 kr	48 344 kr	48 344 kr
Total Annuity	**840 432 kr**	**707 887 kr**	**824 061 kr**	**802 960 kr**	**670 415 kr**	**954 766 kr**	**854 674 kr**

Cumulative cost

Year	CO2 Direct & DH	CO2 Indirect & DH	Existing system	CO2 Direct & DH & Export	CO2 Indirect & DH & Export	NH3 & DH	NH3 HP & DH
0	6 867 500 kr	3 939 000 kr	- kr	7 057 500 kr	4 129 000 kr	4 351 000 kr	5 506 000 kr
1	7 223 768 kr	4 328 402 kr	675 889 kr	7 371 476 kr	4 476 110 kr	4 919 960 kr	5 929 133 kr
2	7 585 380 kr	4 723 645 kr	1 361 916 kr	7 690 162 kr	4 828 427 kr	5 497 454 kr	6 358 613 kr
3	7 952 417 kr	5 124 817 kr	2 058 234 kr	8 013 628 kr	5 186 028 kr	6 083 611 kr	6 794 535 kr
4	8 324 959 kr	5 532 006 kr	2 764 997 kr	8 341 946 kr	5 548 993 kr	6 678 560 kr	7 236 995 kr
5	8 810 817 kr	6 053 031 kr	3 751 682 kr	8 782 917 kr	6 025 132 kr	7 551 754 kr	7 955 414 kr
6	9 194 619 kr	6 472 528 kr	4 479 806 kr	9 121 159 kr	6 399 068 kr	8 164 685 kr	8 411 248 kr
7	9 672 966 kr	6 987 104 kr	5 218 853 kr	9 553 261 kr	6 867 400 kr	8 786 810 kr	8 873 920 kr
8	10 068 368 kr	7 419 280 kr	5 968 985 kr	9 901 726 kr	7 252 639 kr	9 418 268 kr	9 343 532 kr
9	10 469 701 kr	7 857 939 kr	6 730 369 kr	10 255 418 kr	7 643 655 kr	10 059 197 kr	9 820 188 kr
10	11 097 557 kr	8 523 680 kr	7 886 152 kr	10 834 918 kr	8 261 040 kr	11 092 718 kr	10 686 972 kr
11	11 511 021 kr	8 975 597 kr	8 670 549 kr	11 199 300 kr	8 663 875 kr	11 753 019 kr	11 178 035 kr
12	11 930 687 kr	9 434 292 kr	9 466 712 kr	11 569 148 kr	9 072 753 kr	12 423 225 kr	11 676 464 kr
13	12 356 648 kr	9 899 868 kr	10 274 817 kr	11 944 544 kr	9 487 764 kr	13 103 483 kr	12 182 369 kr
14	12 887 538 kr	10 470 969 kr	11 095 044 kr	12 424 110 kr	10 007 541 kr	13 793 946 kr	12 695 863 kr
15	13 451 397 kr	11 075 640 kr	12 240 132 kr	12 935 876 kr	10 560 119 kr	14 807 323 kr	13 529 618 kr
16	13 896 814 kr	11 562 483 kr	13 085 150 kr	13 328 419 kr	10 994 087 kr	15 518 655 kr	14 058 632 kr
17	14 348 914 kr	12 056 628 kr	13 942 844 kr	13 726 850 kr	11 434 564 kr	16 240 657 kr	14 595 581 kr
18	14 807 794 kr	12 558 186 kr	14 813 403 kr	14 131 257 kr	11 881 649 kr	16 973 489 kr	15 140 585 kr
19	15 273 558 kr	13 067 267 kr	15 697 020 kr	14 541 731 kr	12 335 440 kr	17 717 313 kr	15 693 764 kr
20	15 734 880 kr	13 572 556 kr	16 593 892 kr	14 946 934 kr	12 784 609 kr	18 472 295 kr	16 255 240 kr

System technical performance:

	CO2 Direct & DH	CO2 Indirect & DH	Existing system	CO2 Direct & DH & Export	CO2 Indirect & DH & Export	NH3 & DH	NH3 HP & DH
COP							
Refrigeration	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Heating	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Combined	**3,8**	**3,4**	**1,8**	**3,8**	**3,4**	**2,1**	**3,5**
Energy consumption per year							
Refrigeration	0	0	0	0	0	0	0
Heating	0	0	0	0	0	0	0
Total	**344**	**387**	**743**	**344**	**387**	**644**	**374**

Selected system settings:

	CO2 Direct & DH	CO2 Indirect & DH	Existing system	CO2 Direct & DH & Export	CO2 Indirect & DH & Export	NH3 & DH	NH3 HP & DH
Distribution system							
Header material	Copper	Plastic	Plastic	Copper	Plastic	Plastic	Plastic
Rink piping material	Copper	Plastic	Plastic	Copper	Plastic	Plastic	Plastic
Thermal concrete layer	Disabled	Disabled	Disabled	Disabled	Disabled	Disabled	Disabled
Optional modules							
Heat recovery	Enabled	Enabled	Enabled	Enabled	Enabled	Enabled	Enabled
Geothermal heat storage	Disabled	Disabled	Disabled	Disabled	Disabled	Disabled	Disabled
Heat export	Disabled	Disabled	Disabled	Enabled	Enabled	Disabled	Disabled
External heat source	District heating	District heating	District Heating	District heating	District heating	District Heating	HP&DH

System comparison 5

Input data used in LCC	
Important information	

Scenario & sensitivity analysis

Cost of capital	3,5	%
Investment price level	100	%
Residual value price level	100	%
Periodic service price level	100	%
Yearly service price level	100	%
Electricity price level	100	%
District heating price level	100	%
Heat export to client price level	100	%

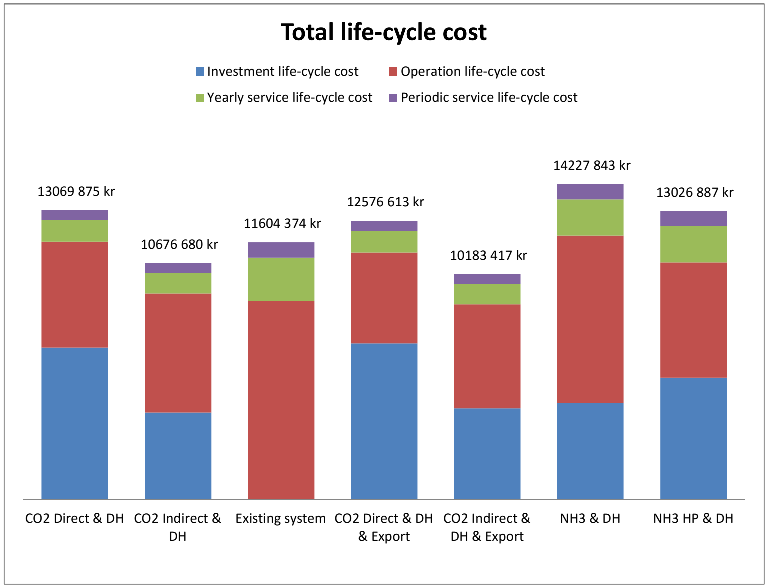
Displayed currency:	SEK
Currency multiplier:	1

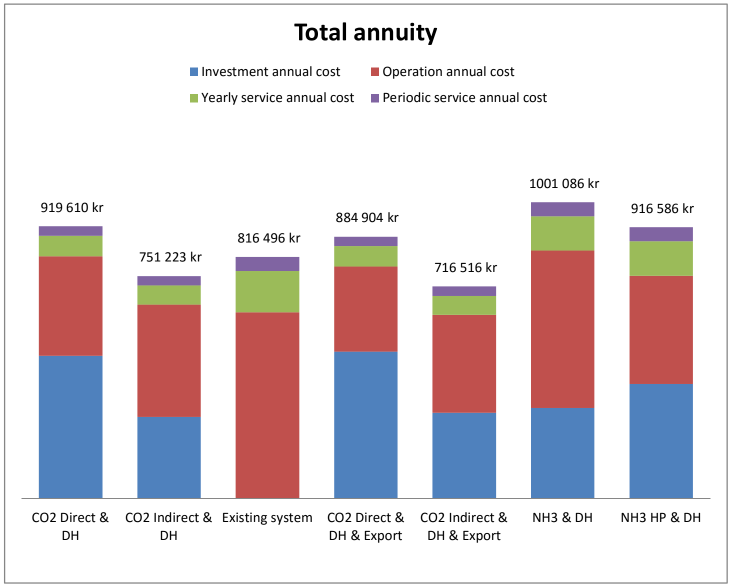
Residual value price escalation %:	0
Periodic service price escalation %:	1,5
Yearly service price escalation %:	1,5
Electricity price escalation %:	1,5
District heating price escalation %:	1,5
Heat export to client price esc. %:	1,5

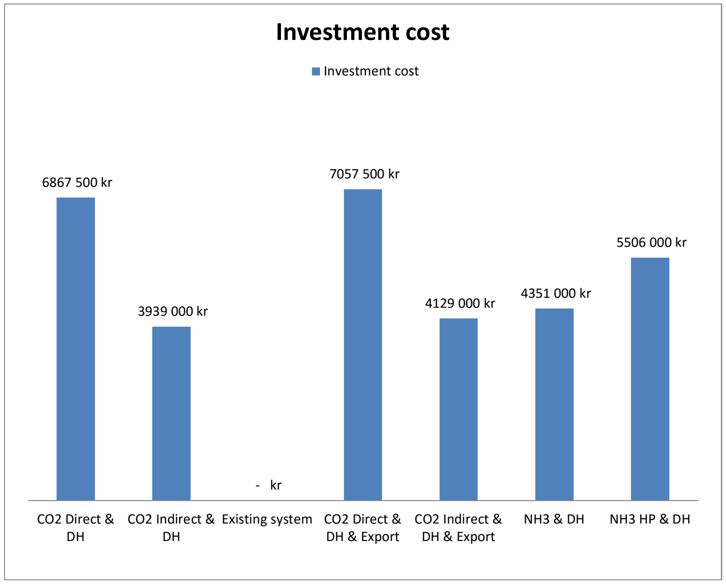
Comment:

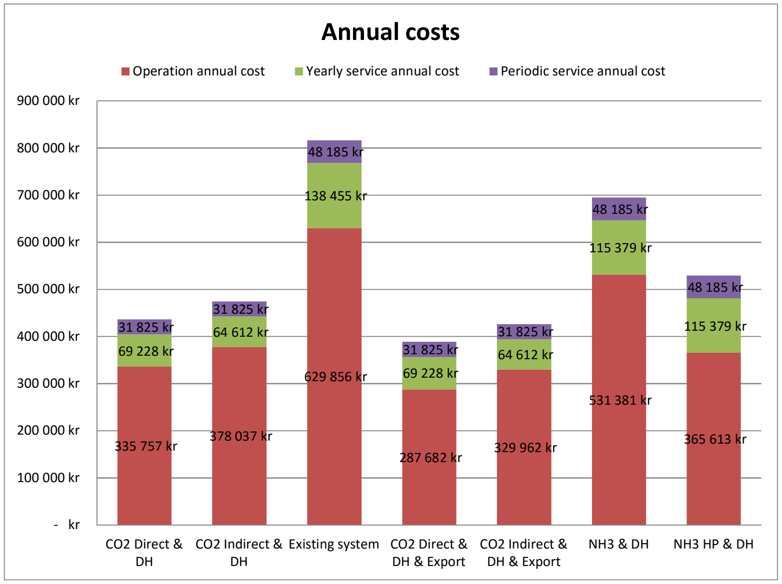
Normal economic outlook. Discount rate is increased to 3,5%.

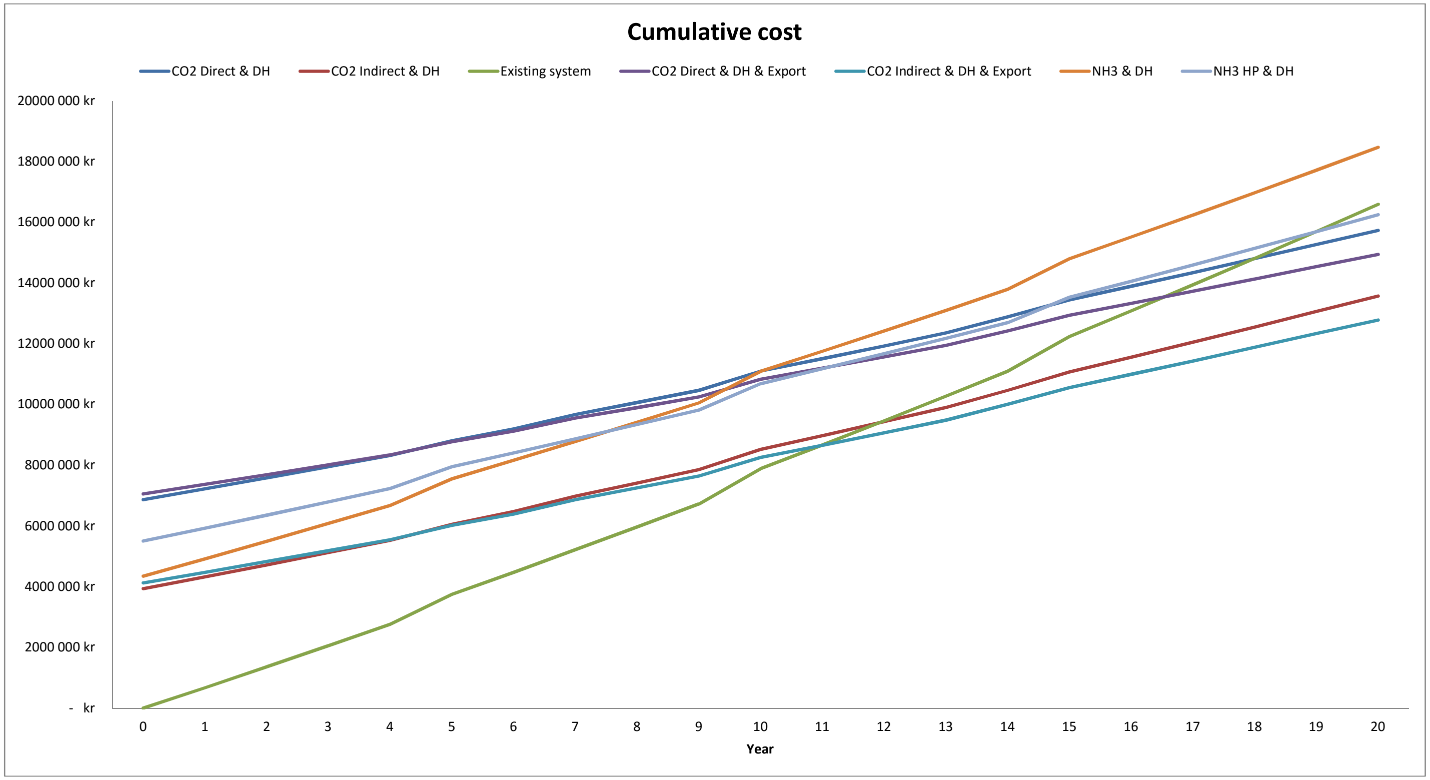
CO_2-indirect performs best in this scenario, even though its benefits become smaller.


Total life-cycle cost
Investment life-cycle cost
Operation life-cycle cost
Yearly service life-cycle cost
Periodic service life-cycle cost
13069 875 kr
10676 680 kr
11604 374 kr
12576 613 kr
10183 417 kr
14227 843 kr
13026 887 kr
CO2 Direct & DH
CO2 Indirect & DH
Existing system
CO2 Direct & DH & Export
CO2 Indirect & DH & Export
NH3 & DH
NH3 HP & DH


Total annuity
Investment annual cost
Operation annual cost
Yearly service annual cost
Periodic service annual cost
919 610 kr
751 223 kr
816 496 kr
884 904 kr
716 516 kr
1001 086 kr
916 586 kr
CO2 Direct & DH
CO2 Indirect & DH
Existing system
CO2 Direct & DH & Export
CO2 Indirect & DH & Export
NH3 & DH
NH3 HP & DH


Investment cost
Investment cost
6867 500 kr
3939 000 kr
- kr
7057 500 kr
4129 000 kr
4351 000 kr
5506 000 kr
CO2 Direct & DH
CO2 Indirect & DH
Existing system
CO2 Direct & DH & Export
CO2 Indirect & DH & Export
NH3 & DH
NH3 HP & DH


Annual costs
Operation annual cost
Yearly service annual cost
Periodic service annual cost
900 000 kr
800 000 kr
700 000 kr
600 000 kr
500 000 kr
400 000 kr
300 000 kr
200 000 kr
100 000 kr
- kr
31 825 kr
69 228 kr
335 757 kr
31 825 kr
64 612 kr
378 037 kr
48 185 kr
138 455 kr
629 856 kr
31 825 kr
69 228 kr
287 682 kr
31 825 kr
64 612 kr
329 962 kr
48 185 kr
115 379 kr
531 381 kr
48 185 kr
115 379 kr
365 613 kr
CO2 Direct & DH
CO2 Indirect & DH
Existing system
CO2 Direct & DH & Export
CO2 Indirect & DH & Export
NH3 & DH
NH3 HP & DH



Cumulative cost
CO2 Direct & DH
CO2 Indirect & DH
Existing system
CO2 Direct & DH & Export
CO2 Indirect & DH & Export
NH3 & DH
NH3 HP & DH
20000 000 kr
18000 000 kr
16000 000 kr
14000 000 kr
12000 000 kr
10000 000 kr
8000 000 kr
6000 000 kr
4000 000 kr
2000 000 kr
- kr
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
Year

System financial performance:

	CO2 Direct & DH	CO2 Indirect & DH	Existing system	CO2 Direct & DH & Export	CO2 Indirect & DH & Export	NH3 & DH	NH3 HP & DH
Starting point							
Investment cost	6 867 500 kr	3 939 000 kr	- kr	7 057 500 kr	4 129 000 kr	4 351 000 kr	5 506 000 kr
Economic lifespan	20	20	20	20	20	20	20
Life-cycle costs							
Investment life-cycle cost	6 861 756 kr	3 933 256 kr	- kr	7 051 756 kr	4 123 256 kr	4 351 000 kr	5 506 000 kr
Operation life-cycle cost	4 771 918 kr	5 372 815 kr	8 951 770 kr	4 088 655 kr	4 689 553 kr	7 552 202 kr	5 196 246 kr
Yearly service life-cycle cost	983 890 kr	918 297 kr	1 967 780 kr	983 890 kr	918 297 kr	1 639 817 kr	1 639 817 kr
Periodic service life-cycle cost	452 311 kr	452 311 kr	684 825 kr	452 311 kr	452 311 kr	684 825 kr	684 825 kr
Total Life-cycle cost	**13 069 875 kr**	**10 676 680 kr**	**11 604 374 kr**	**12 576 613 kr**	**10 183 417 kr**	**14 227 843 kr**	**13 026 887 kr**
Equivalent Annual Cost							
Investment annual cost	482 801 kr	276 748 kr	- kr	496 169 kr	290 117 kr	306 141 kr	387 408 kr
Operation annual cost	335 757 kr	378 037 kr	629 856 kr	287 682 kr	329 962 kr	531 381 kr	365 613 kr
Yearly service annual cost	69 228 kr	64 612 kr	138 455 kr	69 228 kr	64 612 kr	115 379 kr	115 379 kr
Periodic service annual cost	31 825 kr	31 825 kr	48 185 kr	31 825 kr	31 825 kr	48 185 kr	48 185 kr
Total Annuity	**919 610 kr**	**751 223 kr**	**816 496 kr**	**884 904 kr**	**716 516 kr**	**1 001 086 kr**	**916 586 kr**

Cumulative cost

Year	CO2 Direct & DH	CO2 Indirect & DH	Existing system	CO2 Direct & DH & Export	CO2 Indirect & DH & Export	NH3 & DH	NH3 HP & DH
0	6 867 500 kr	3 939 000 kr	- kr	7 057 500 kr	4 129 000 kr	4 351 000 kr	5 506 000 kr
1	7 223 768 kr	4 328 402 kr	675 889 kr	7 371 476 kr	4 476 110 kr	4 919 960 kr	5 929 133 kr
2	7 585 380 kr	4 723 645 kr	1 361 916 kr	7 690 162 kr	4 828 427 kr	5 497 454 kr	6 358 613 kr
3	7 952 417 kr	5 124 817 kr	2 058 234 kr	8 013 628 kr	5 186 028 kr	6 083 611 kr	6 794 535 kr
4	8 324 959 kr	5 532 006 kr	2 764 997 kr	8 341 946 kr	5 548 993 kr	6 678 560 kr	7 236 995 kr
5	8 810 817 kr	6 053 031 kr	3 751 682 kr	8 782 917 kr	6 025 132 kr	7 551 754 kr	7 955 414 kr
6	9 194 619 kr	6 472 528 kr	4 479 806 kr	9 121 159 kr	6 399 068 kr	8 164 685 kr	8 411 248 kr
7	9 672 966 kr	6 987 104 kr	5 218 853 kr	9 553 261 kr	6 867 400 kr	8 786 810 kr	8 873 920 kr
8	10 068 368 kr	7 419 280 kr	5 968 985 kr	9 901 726 kr	7 252 639 kr	9 418 268 kr	9 343 532 kr
9	10 469 701 kr	7 857 939 kr	6 730 369 kr	10 255 418 kr	7 643 655 kr	10 059 197 kr	9 820 188 kr
10	11 097 557 kr	8 523 680 kr	7 886 152 kr	10 834 918 kr	8 261 040 kr	11 092 718 kr	10 686 972 kr
11	11 511 021 kr	8 975 597 kr	8 670 549 kr	11 199 300 kr	8 663 875 kr	11 753 019 kr	11 178 035 kr
12	11 930 687 kr	9 434 292 kr	9 466 712 kr	11 569 148 kr	9 072 753 kr	12 423 225 kr	11 676 464 kr
13	12 356 648 kr	9 899 868 kr	10 274 817 kr	11 944 544 kr	9 487 764 kr	13 103 483 kr	12 182 369 kr
14	12 887 538 kr	10 470 969 kr	11 095 044 kr	12 424 110 kr	10 007 541 kr	13 793 946 kr	12 695 863 kr
15	13 451 397 kr	11 075 640 kr	12 240 132 kr	12 935 876 kr	10 560 119 kr	14 807 323 kr	13 529 618 kr
16	13 896 814 kr	11 562 483 kr	13 085 150 kr	13 328 419 kr	10 994 087 kr	15 518 655 kr	14 058 632 kr
17	14 348 914 kr	12 056 628 kr	13 942 844 kr	13 726 850 kr	11 434 564 kr	16 240 657 kr	14 595 581 kr
18	14 807 794 kr	12 558 186 kr	14 813 403 kr	14 131 257 kr	11 881 649 kr	16 973 489 kr	15 140 585 kr
19	15 273 558 kr	13 067 267 kr	15 697 020 kr	14 541 731 kr	12 335 440 kr	17 717 313 kr	15 693 764 kr
20	15 734 880 kr	13 572 556 kr	16 593 892 kr	14 946 934 kr	12 784 609 kr	18 472 295 kr	16 255 240 kr

System technical performance:

	CO2 Direct & DH	CO2 Indirect & DH	Existing system	CO2 Direct & DH & Export	CO2 Indirect & DH & Export	NH3 & DH	NH3 HP & DH
COP							
Refrigeration	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Heating	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Combined	**3,8**	**3,4**	**1,8**	**3,8**	**3,4**	**2,1**	**3,5**
Energy consumption per year							
Refrigeration	0	0	0	0	0	0	0
Heating	0	0	0	0	0	0	0
Total	**344**	**387**	**743**	**344**	**387**	**644**	**374**

Selected system settings:

	CO2 Direct & DH	CO2 Indirect & DH	Existing system	CO2 Direct & DH & Export	CO2 Indirect & DH & Export	NH3 & DH	NH3 HP & DH
Distribution system							
Header material	Copper	Plastic	Plastic	Copper	Plastic	Plastic	Plastic
Rink piping material	Copper	Plastic	Plastic	Copper	Plastic	Plastic	Plastic
Thermal concrete layer	Disabled	Disabled	Disabled	Disabled	Disabled	Disabled	Disabled
Optional modules							
Heat recovery	Enabled	Enabled	Enabled	Enabled	Enabled	Enabled	Enabled
Geothermal heat storage	Disabled	Disabled	Disabled	Disabled	Disabled	Disabled	Disabled
Heat export	Disabled	Disabled	Disabled	Enabled	Enabled	Disabled	Disabled
External heat source	District heating	District heating	District Heating	District heating	District heating	District Heating	HP&DH

System comparison 6

Input data used in LCC	
Important information	

Scenario & sensitivity analysis

Cost of capital	2,5	%
Investment price level	100	%
Residual value price level	100	%
Periodic service price level	100	%
Yearly service price level	100	%
Electricity price level	100	%
District heating price level	100	%
Heat export to client price level	100	%

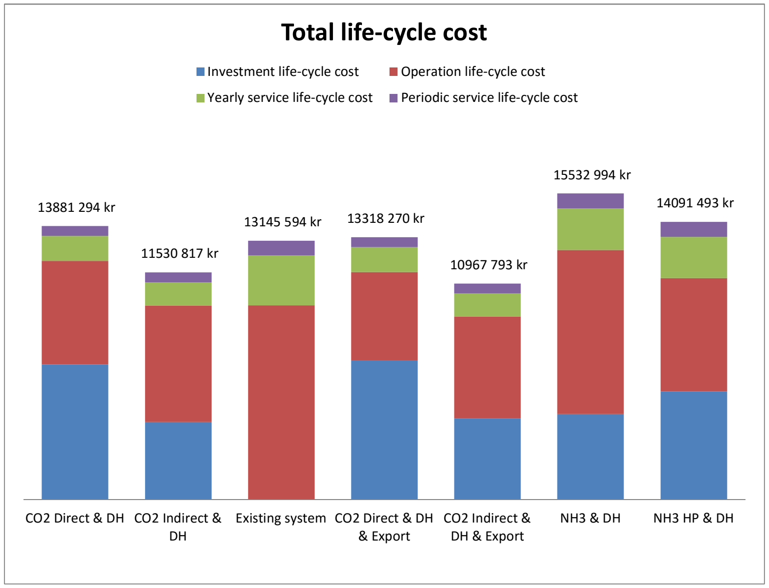
Displayed currency:	SEK
Currency multiplier:	1

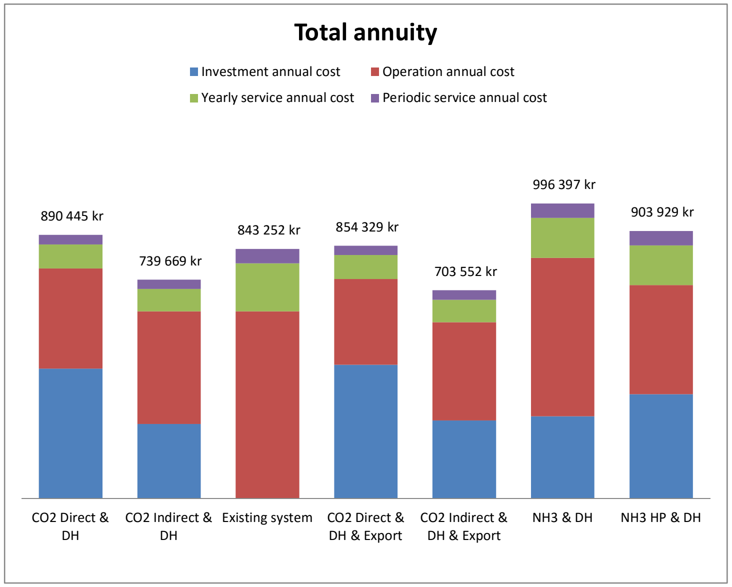
Residual value price escalation %:	0
Periodic service price escalation %:	1,5
Yearly service price escalation %:	3
Electricity price escalation %:	1,5
District heating price escalation %:	1,5
Heat export to client price esc. %:	1,5

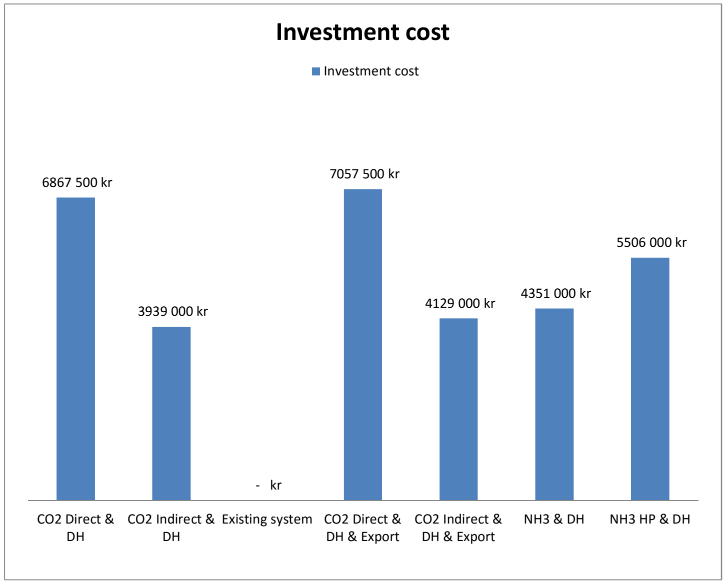
Comment:

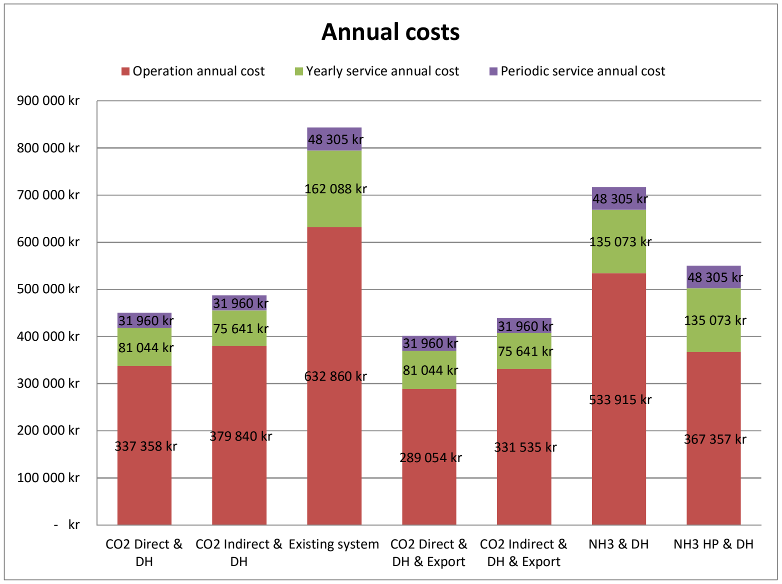
Same setting as in normal economic outlook, with the exception that yearly service costs escalate with 3% each year.

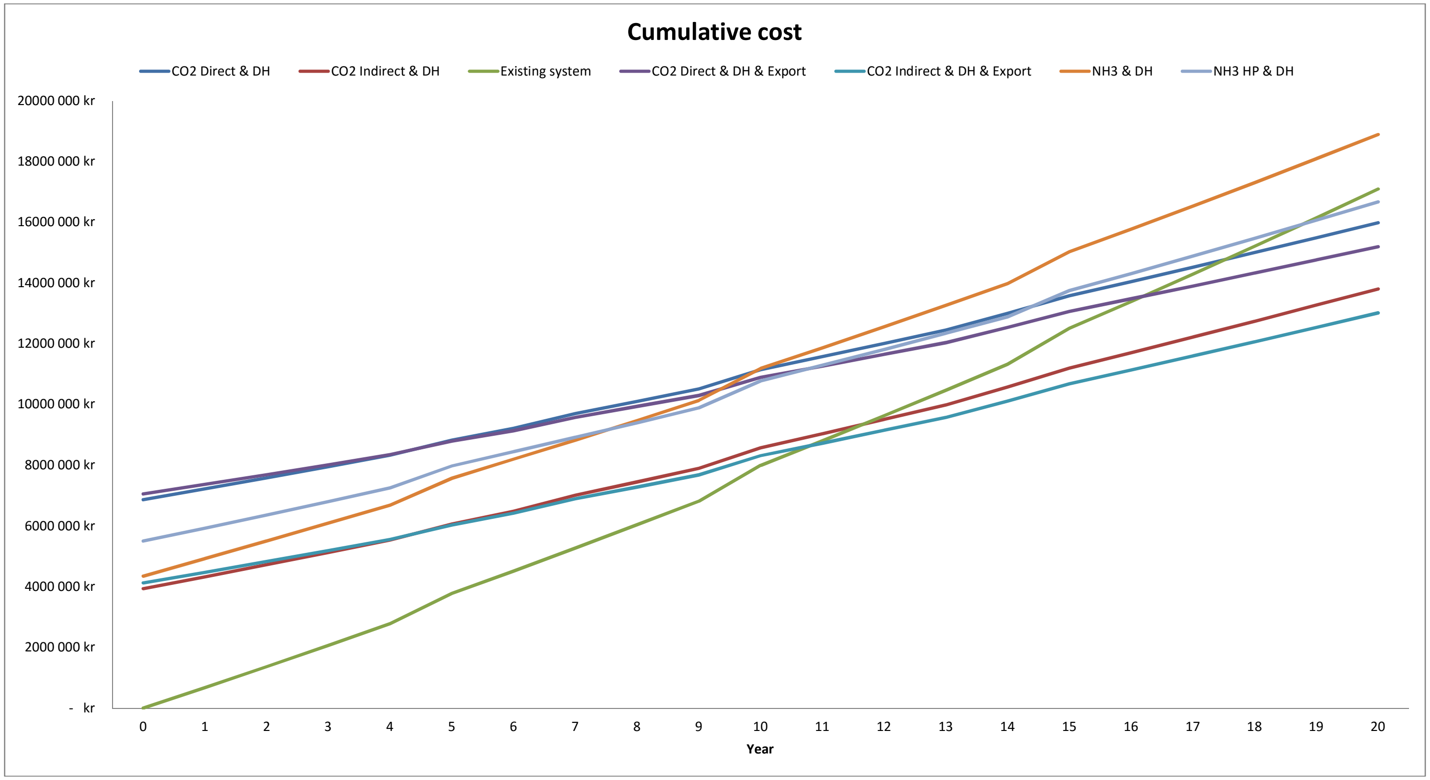
This sensitivity analysis also describes a more probable scenario for the existing system. CO2-indirect is again the favorable option here, and CO2 direct at normal economic outlook from Appendix 1 performs also well in comparison to the existing system in this analysis round.


Total life-cycle cost
Investment life-cycle cost
Operation life-cycle cost
Yearly service life-cycle cost
Periodic service life-cycle cost
13881 294 kr
11530 817 kr
13145 594 kr
13318 270 kr
10967 793 kr
15532 994 kr
14091 493 kr
CO2 Direct & DH
CO2 Indirect & DH
Existing system
CO2 Direct & DH & Export
CO2 Indirect & DH & Export
NH3 & DH
NH3 HP & DH


Total annuity
Investment annual cost
Operation annual cost
Yearly service annual cost
Periodic service annual cost
890 445 kr
739 669 kr
843 252 kr
854 329 kr
703 552 kr
996 397 kr
903 929 kr
CO2 Direct & DH
CO2 Indirect & DH
Existing system
CO2 Direct & DH & Export
CO2 Indirect & DH & Export
NH3 & DH
NH3 HP & DH


Investment cost
Investment cost
6867 500 kr
3939 000 kr
- kr
7057 500 kr
4129 000 kr
4351 000 kr
5506 000 kr
CO2 Direct & DH
CO2 Indirect & DH
Existing system
CO2 Direct & DH & Export
CO2 Indirect & DH & Export
NH3 & DH
NH3 HP & DH


Annual costs
Operation annual cost
Yearly service annual cost
Periodic service annual cost
900 000 kr
800 000 kr
700 000 kr
600 000 kr
500 000 kr
400 000 kr
300 000 kr
200 000 kr
100 000 kr
- kr
31 960 kr
81 044 kr
337 358 kr
31 960 kr
75 641 kr
379 840 kr
48 305 kr
162 088 kr
632 860 kr
31 960 kr
81 044 kr
289 054 kr
31 960 kr
75 641 kr
331 535 kr
48 305 kr
135 073 kr
533 915 kr
48 305 kr
135 073 kr
367 357 kr
CO2 Direct & DH
CO2 Indirect & DH
Existing system
CO2 Direct & DH & Export
CO2 Indirect & DH & Export
NH3 & DH
NH3 HP & DH


Cumulative cost
CO2 Direct & DH
CO2 Indirect & DH
Existing system
CO2 Direct & DH & Export
CO2 Indirect & DH & Export
NH3 & DH
NH3 HP & DH
20000 000 kr
18000 000 kr
16000 000 kr
14000 000 kr
12000 000 kr
10000 000 kr
8000 000 kr
6000 000 kr
4000 000 kr
2000 000 kr
- kr
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
Year

System financial performance:

	CO2 Direct & DH	CO2 Indirect & DH	Existing system	CO2 Direct & DH & Export	CO2 Indirect & DH & Export	NH3 & DH	NH3 HP & DH
Starting point							
Investment cost	6 867 500 kr	3 939 000 kr	- kr	7 057 500 kr	4 129 000 kr	4 351 000 kr	5 506 000 kr
Economic lifespan	20	20	20	20	20	20	20
Life-cycle costs							
Investment life-cycle cost	6 860 525 kr	3 932 025 kr	- kr	7 050 525 kr	4 122 025 kr	4 351 000 kr	5 506 000 kr
Operation life-cycle cost	5 259 134 kr	5 921 383 kr	9 865 751 kr	4 506 110 kr	5 168 359 kr	8 323 287 kr	5 726 786 kr
Yearly service life-cycle cost	1 263 405 kr	1 179 178 kr	2 526 809 kr	1 263 405 kr	1 179 178 kr	2 105 674 kr	2 105 674 kr
Periodic service life-cycle cost	498 231 kr	498 231 kr	753 033 kr	498 231 kr	498 231 kr	753 033 kr	753 033 kr
Total Life-cycle cost	**13 881 294 kr**	**11 530 817 kr**	**13 145 594 kr**	**13 318 270 kr**	**10 967 793 kr**	**15 532 994 kr**	**14 091 493 kr**
Equivalent Annual Cost							
Investment annual cost	440 083 kr	252 228 kr	- kr	452 271 kr	264 416 kr	279 104 kr	353 194 kr
Operation annual cost	337 358 kr	379 840 kr	632 860 kr	289 054 kr	331 535 kr	533 915 kr	367 357 kr
Yearly service annual cost	81 044 kr	75 641 kr	162 088 kr	81 044 kr	75 641 kr	135 073 kr	135 073 kr
Periodic service annual cost	31 960 kr	31 960 kr	48 305 kr	31 960 kr	31 960 kr	48 305 kr	48 305 kr
Total Annuity	**890 445 kr**	**739 669 kr**	**843 252 kr**	**854 329 kr**	**703 552 kr**	**996 397 kr**	**903 929 kr**

Cumulative cost

Year	CO2 Direct & DH	CO2 Indirect & DH	Existing system	CO2 Direct & DH & Export	CO2 Indirect & DH & Export	NH3 & DH	NH3 HP & DH
0	6 867 500 kr	3 939 000 kr	- kr	7 057 500 kr	4 129 000 kr	4 351 000 kr	5 506 000 kr
1	7 224 668 kr	4 329 242 kr	677 689 kr	7 372 376 kr	4 476 950 kr	4 921 460 kr	5 930 633 kr
2	7 588 121 kr	4 726 203 kr	1 367 397 kr	7 692 902 kr	4 830 984 kr	5 502 022 kr	6 363 180 kr
3	7 957 980 kr	5 130 009 kr	2 069 361 kr	8 019 191 kr	5 191 220 kr	6 092 883 kr	6 803 807 kr
4	8 334 371 kr	5 540 791 kr	2 783 821 kr	8 351 358 kr	5 557 778 kr	6 694 247 kr	7 252 682 kr
5	8 825 148 kr	6 066 407 kr	3 780 345 kr	8 797 249 kr	6 038 508 kr	7 575 640 kr	7 979 300 kr
6	9 214 987 kr	6 491 538 kr	4 520 543 kr	9 141 527 kr	6 418 078 kr	8 198 632 kr	8 445 195 kr
7	9 700 535 kr	7 012 836 kr	5 273 992 kr	9 580 831 kr	6 893 132 kr	8 832 760 kr	8 919 870 kr
8	10 104 354 kr	7 452 868 kr	6 040 958 kr	9 937 713 kr	7 286 226 kr	9 478 245 kr	9 403 509 kr
9	10 515 371 kr	7 900 563 kr	6 821 708 kr	10 301 087 kr	7 686 280 kr	10 135 312 kr	9 896 304 kr
10	11 154 229 kr	8 576 574 kr	7 999 496 kr	10 891 590 kr	8 313 934 kr	11 187 171 kr	10 781 426 kr
11	11 580 070 kr	9 040 042 kr	8 808 647 kr	11 268 349 kr	8 728 321 kr	11 868 101 kr	11 293 117 kr
12	12 013 545 kr	9 511 626 kr	9 632 427 kr	11 652 006 kr	9 150 087 kr	12 561 321 kr	11 814 560 kr
13	12 454 804 kr	9 991 481 kr	10 471 130 kr	12 042 700 kr	9 579 377 kr	13 267 078 kr	12 345 964 kr
14	13 002 545 kr	10 578 308 kr	11 325 057 kr	12 539 117 kr	10 114 880 kr	13 985 624 kr	12 887 541 kr
15	13 584 867 kr	11 200 212 kr	12 507 074 kr	13 069 346 kr	10 684 691 kr	15 029 775 kr	13 752 069 kr
16	14 050 428 kr	11 705 856 kr	13 392 378 kr	13 482 033 kr	11 137 460 kr	15 774 679 kr	14 314 655 kr
17	14 524 417 kr	12 220 432 kr	14 293 851 kr	13 902 353 kr	11 598 368 kr	16 533 163 kr	14 888 087 kr
18	15 007 003 kr	12 744 114 kr	15 211 821 kr	14 330 467 kr	12 067 578 kr	17 305 504 kr	15 472 600 kr
19	15 498 360 kr	13 277 082 kr	16 146 625 kr	14 766 534 kr	12 545 256 kr	18 091 984 kr	16 068 434 kr
20	15 987 238 kr	13 808 089 kr	17 098 607 kr	15 199 291 kr	13 020 143 kr	18 892 891 kr	16 675 836 kr

System technical performance:

	CO2 Direct & DH	CO2 Indirect & DH	Existing system	CO2 Direct & DH & Export	CO2 Indirect & DH & Export	NH3 & DH	NH3 HP & DH
COP							
Refrigeration	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Heating	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Combined	**3,8**	**3,4**	**1,8**	**3,8**	**3,4**	**2,1**	**3,5**
Energy consumption per year							
Refrigeration	0	0	0	0	0	0	0
Heating	0	0	0	0	0	0	0
Total	**344**	**387**	**743**	**344**	**387**	**644**	**374**

Selected system settings:

	CO2 Direct & DH	CO2 Indirect & DH	Existing system	CO2 Direct & DH & Export	CO2 Indirect & DH & Export	NH3 & DH	NH3 HP & DH
Distribution system							
Header material	Copper	Plastic	Plastic	Copper	Plastic	Plastic	Plastic
Rink piping material	Copper	Plastic	Plastic	Copper	Plastic	Plastic	Plastic
Thermal concrete layer	Disabled	Disabled	Disabled	Disabled	Disabled	Disabled	Disabled
Optional modules							
Heat recovery	Enabled	Enabled	Enabled	Enabled	Enabled	Enabled	Enabled
Geothermal heat storage	Disabled	Disabled	Disabled	Disabled	Disabled	Disabled	Disabled
Heat export	Disabled	Disabled	Disabled	Enabled	Enabled	Disabled	Disabled
External heat source	District heating	District heating	District Heating	District heating	District heating	District Heating	HP&DH